A Review of Models in Support of Oil and Gas Exploration off the North Coast of British Columbia

M.G.G. Foreman, L. Beauchemin, J.Y. Cherniawsky, M.A. Peña,
P. F. Cummins, and G. Sutherland

Institute of Ocean Sciences
Fisheries and Oceans Canada
P.O. Box 6000
Sidney, B.C. V8L 4B2

2005

Canadian Technical Report of
Fisheries and Aquatic Sciences 2612

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Canadian Technical Report of Fisheries and Aquatic Sciences

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106-01444/

Canadian Technical Report of
Fisheries and Aquatic Sciences 2612

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A REWIEW OF MODELS IN SUPPORT OF OIL AND GAS EXPLORATION OFF THE NORTH COAST OF BRITISH COLUMBIA

by

M.G.G. Foreman, L. Beauchemin, J.Y. Cherniawsky, M.A. Peña,
P. F. Cummins, and G. Sutherland

Institute of Ocean Sciences
Fisheries and Oceans Canada
P.O. Box 6000
Sidney, B.C. V8L 4B2

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Cat. No. Fs97-6/2612E ISSN 0706-6457

Correct citation for this publication:

Foreman, M.G.G., Beauchemin, L., Cherniawsky, J.Y., Peña, M.A., Cummins, P.F. and Sutherland, G. 2005. A review of models in support of oil and gas exploration off the north coast of British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 2612: v + 58 p.

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ABSTRACT

Foreman, M.G.G., Beauchemin, L., Cherniawsky, J.Y., Peña, M.A., Cummins, P.F. and Sutherland, G. 2005. A review of models in support of oil and gas exploration off the north coast of British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 2612: v + 58 p.

A state-of-the-art review of numerical models that would be needed to address scientific and environmental issues related to removing the moratorium on offshore oil and gas exploration for the waters off northern British Columbia is presented. Specific recommendations are made for circulation, ecosystem, oil spill, and drilling mud models. Complementary needs for more observations to validate these models and for the development of both a high resolution surface wave model and a high resolution atmospheric model, are also foreseen. It is anticipated that these recommendations will be useful when future science programs related to oil and gas exploration are developed.

RESUMÉ

Foreman, M.G.G., Beauchemin, L., Cherniawsky, J.Y., Peña, M.A., Cummins, P.F. and Sutherland, G. 2005. A review of models in support of oil and gas exploration off the north coast of British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 2612: v + 58 p.

On présente une étude sur l'état actuel des modèles numériques nécessaires pour aborder les questions scientifiques et environnementales liées à la levée du moratoire sur l'exploration pétrolière et gazière dans les eaux au large de la côte Nord de la Colombie-Britannique. Nous formulons des recommandations spécifiques quant aux modèles de circulation, de l'écosystème, de déversement d'hydrocarbure et de boue de forage. On souligne également la nécessité de recueillir un plus grand nombre d'observations pour valider ces modèles, et pour l'élaboration d'un modèle de vagues de surface à haute résolution et d'un modèle atmosphérique haute résolution. On prévoit que ces recommandations se révéleront utiles à l'avenir lors de l'élaboration des programmes scientifiques liés à l'exploration pétrolière et gazière.

1.0 INTRODUCTION

Coastal oceans are among the most complex environments in the world and the waters off British Columbia are no exception. Highly irregular coastlines, highly variable bathymetry and a circulation that is driven by a complex array of tidal, wind, and buoyancy forcing on a broad range of space and time scales makes it difficult, if not impossible, to obtain detailed pictures of oceanic flows without the use of comprehensive ocean measurements and computer models. Though measurements can reveal important features of the ocean environment, they have limitations. Satellites can provide images almost everywhere every few days but are generally restricted to surface features and, in many cases, to only cloud-free days. In-situ observations, taken either directly from a ship or indirectly via deployed instrumentation such as drifters or current meters, can measure more variables as well as penetrate deeper into the water. However, these measurements are generally sparse both in time and/or space. Numerical ocean models are a means of improving our understanding of ocean processes by interpolating these observations and providing a detailed and realistic view of the ocean. Improved numerical methods, powerful computers and more verification data have advanced the development of ocean modelling in recent years, making it one of the most important tools available to oceanographers. Nevertheless, modelling remains challenging because many processes within the coastal environment, such as sub-grid scale parameterization, and many issues related to model implementation and behaviour, such as the numerical approximation to specific terms in the governing equations, either are still not fully understood (Haidvogel *et al.* 1998) or require improvement.

There are generally three motives for modelling ocean circulation: i) representing past events, i.e., hindcasting; ii) predicting future events, i.e., forecasting; and iii) providing a better understanding of the underlying dynamics, i.e., process studies. Properly evaluated hindcast models are a means of interpolating between observations (if they exist) and providing a more complete picture of the evolution of the ocean for a period of time in the past. An example is the retrospective analysis (hindcast) of waves in the Queen Charlotte Basin conducted by MacLaren (1993). Forecast model simulations are similar except they attempt to represent the ocean circulation for some time in the future. Several examples are listed in section 2. Each generally requires an extensive array of observations so that the initial conditions at the beginning of the forecast are accurate, and a reliable weather forecast so that the future atmospheric forcing is credible. Finally, ocean models can also be used for process studies by varying, for example, the model forcing or specific parameters within the mathematical equations, and analysing the model results as a means of better understanding the underlying physics. Examples are the modeling carried out by Di Lorenzo *et al.* (2005) to elucidate the generation mechanism behind the Haida Eddies that are typically formed each winter off Cape St. James, and by Cummins and Oey (1997) to study the nature of internal tides in northern BC waters.

The purpose of this report is to present a state-of-the-art review of numerical models that would be needed to address scientific and environmental issues related to removing the moratorium on offshore oil and gas exploration for the waters off northern British Columbia. In order to better understand the ocean circulation dynamics of the region, we foresee a need for both hindcasting and process study models. Forecasting models may also be required if sufficient hydro-carbon reserves were found to warrant production. Specific recommendations are made for circulation, ecosystem, oil spill, and drilling mud models. Complementary needs for more observations to validate these models and for the development of both a high resolution surface wave model and a high resolution atmospheric model, are also foreseen. It is hoped that these recommendations will be useful when future science programs related to oil and gas exploration are developed.

2.0 BACKGROUND

2.1 PHYSICAL PROCESSES

Thomson (1981) describes the Queen Charlotte Basin (henceforth QCB, Figure 1) as a coastal seaway consisting of Dixon Entrance in the north, Queen Charlotte Sound in the south, and Hecate Strait, as the middle semi-enclosed sea between mainland BC and the Queen Charlotte Islands. The physical oceanography of the basin has been reviewed by Dodimead (1980), Tabata (1980), and Thomson (1981) based largely on data collected by the Pacific Oceanographic Group during the 1950s and 60s and more recently by scientists from the Institute of Ocean Sciences (DFO) (Report of the Expert Panel on Science Issues Related to Oil and Gas Activities, Offshore British Columbia, 2004; hereafter referred to as RC 2004). Water depths in most of the basin are greater than 100 m, with maximum depths reaching more than 400 m. Several submarine canyons, such as Moresby Trough and Dixon Entrance, provide important pathways for deep nutrients onto the continental shelf. Although much of the seabed is covered by silty sediment, there are also rock outcrops, boulder beds, sands and several unique siliceous sponge reefs. This rugged seabed poses several potential hazards to marine activities: slope instability, moving sediment, shallow gas, and active faulting (RC 2004). Tsunamis have been recorded in the Queen Charlotte Basin, but their wave heights are smaller than those of storm waves. Though the effects of the anticipated Cascadia Subduction megathrust (M = 9) earthquake and tsunami have not been studied for this area, tsunami wave heights and currents are expected to be smaller here than the 8-12 m heights and the up-to 30 knot currents projected for the West Coast of Vancouver Island (Cherniawsky *et al.* 2004).

2.1.1 Wind and wave conditions

The QCB experiences some of the most extreme wind and wave conditions in Canada. Frequent and intense storms give rise to extreme sea state conditions, especially during the winter months when Aleutian low pressure systems are prevalent (RC 2004). Annual mean wind speeds usually exceed 10 m/s, with monthly mean wind speeds in winter reaching 20 m/s (Cherniawsky and Crawford 1996) and gusts occasionally reach 55m/s. Annual mean wave heights in the QCB range from more than 2.5 m at the mouth of Queen Charlotte Sound, to about 2 m in the central portion of the Sound, and about 1.5 m in Dixon Entrance. However "monster waves" of more than 25 m may occur during extreme storms which can develop in less than 8 hours (Gower *et al.* 1994).

During the winter, storms occur in the Queen Charlotte Basin every 2-3 days. Field studies conducted near Cape St. James by Masson (1996) have demonstrated that strong tidal currents can significantly amplify wave heights. There are also areas near the Queen Charlotte Islands where wave and current refraction are significant. In a retrospective analysis of waves in the Queen Charlotte Basin between 1957 and 1989, MacLaren (1993) estimated the 100-year significant wave height, Hs (defined as the average height of the highest 1/3 of the waves), to be about 13 m and the highest wave height, Hmax (to occur every 100 years), to be about 25m. Cretney *et al.* (2002) noted, however, that these estimates should be updated as they did not factor in the effects of shallow topography (which can amplify extreme waves) or the wave-current interactions documented by Masson (1996). As well as storm frequency and intensity, the speed with which extreme sea states can develop is of particular concern in the Queen Charlotte Basin. For example, one consequence of climate change in the Pacific Ocean is that the increased frequency of large storms may be decreasing the return periods for such extreme events.

2.1.2 Tidal currents

The tide floods into the main portion of the Queen Charlotte Basin from two directions: north eastward through Queen Charlotte Sound and southward from Dixon Entrance (Thomson, 1981). These flows meet in the northern part of Hecate Strait, on the north-east side of the Queen Charlotte Islands. Tides within the basin are generally classified as 'mixed semidiurnal,' meaning that there are usually two (unequal) high tides and two (unequal) low tides per day. Mean tidal ranges at the mouth of Queen Charlotte Sound and the western end of Dixon Entrance are generally around 3.0 - 3.5 m, with the tidal range increasing eastward. In the central portion of Hecate Strait, the tidal range is more than 4.5 m, and ranges in excess of 7.0 m occur near Prince Rupert and Queen Charlotte City (Thomson, 1981; Cretney *et al.* 2002). In the central part of Hecate Strait, tidal currents average about 1 knot (0.5 m/s). Elsewhere in the Queen Charlotte Basin, near-bottom tidal currents are usually of the order of 15-25 cm/s (Thomson 1981). In other areas such as off Rose Point in the north and off Cape St. James in the south, tidal currents are much stronger and can exceed 4-5 knots (2.0 - 2.5 m/s) (Cretney *et al.* 2002). Also, a process called tidal rectification helps set up a counterclockwise gyre, the Rose Spit Eddy, in eastern Dixon Entrance (Ballantyne *et al.* 1996) and prevailing southward flows off the eastern side of Cape St. James in both summer and winter (Thomson *et al.* 1987). These southward tidally-rectified flows near the Cape are augmented by local winds in summer and by along-strait sub-surface pressure gradients in winter.

In well-mixed water, tidal currents flow at nearly uniform speed at all depths. However, Cretney *et al.* (2002) stated that in some regions within the Queen Charlotte Basin, especially where tidal currents flow across abrupt changes in bottom depth, some of the internal density interfaces set up internal waves. These waves are generated when bottom waters are significantly denser than near-surface waters, and the interface between these two is moved up and down by the tide passing over sloping bottom. Although small in their surface signature, these waves can set up strong tidal currents (Cretney *et al.* 2002). Some of the largest internal tides in British Columbia waters are found in Dixon Entrance and off the entrance to Queen Charlotte Sound (Cummins and Oey 1997). Tidal speeds may reach several knots and both speed and direction of flow differ between surface and deeper waters (Crawford *et al.* 1998).

2.1.3 Non-tidal currents

The circulation in the Queen Charlotte Basin is also affected by winds and river discharge (RC 2004). The influence of river runoff (mainly from the Nass and Skeena Rivers in the northern portion of the basin) is most important in late spring through early summer (April - June) while wind forcing has its greatest influence during the fall and winter months (i.e. October to March). Between 1982 and 1995, the near-surface circulation in the Queen Charlotte Basin was investigated using various types of drifters drogued in the upper 15m of the water column. Observations were also obtained from satellites and moored current meters at nominal depths of 50, 100, and 150 m, as well as 15 m above ocean bottom. The summaries of these studies (Crawford *et al.* 1995, 1999a and Crawford 2001) discuss several regions of particular interest. The Rose Spit and Haïda eddies also play important roles in local water circulation. Though the former occupies a fixed position, the latter detaches from Cape St James and drifts into the Northeast Pacific Ocean, playing a significant role in transferring coastal nutrients and larvae to the deep ocean (Crawford *et al.* 2002b; Mackas *et al.* 2002). However as most of these recent studies were conducted in the spring and summer, there is much less information available on the details of the winter circulation.

Summer current movements are known with sufficient detail to describe the formation of eddies and the influence of wind. Nevertheless, Crawford *et al.* (2002a) state that some oceanographic features

remain poorly understood. Particularly noteworthy are the motion and impact of mid-depth and bottom currents on biota and the nature of late autumn and winter currents at all depths. Although some studies have examined the currents and water properties along the eastern portion of Hecate Strait, there is very little information on the waters of the Inside Passage and adjacent channels. In addition, ocean currents near Cape St. James are subject to intense, yet poorly understood, turbulent mixing of different water masses (Crawford *et al.* 2002a).

2.1.4 Upwelling and Downwelling

In the northern hemisphere, the Earth's rotation turns currents to the right. During the summer when prevailing winds off British Columbia are generally from the north, this means that currents are turned away from the coast. The process wherein these surface waters are replaced all along the coast by deeper, colder water is called upwelling. Winds are the usual forcing mechanism, though tidal mixing may also carry cooler water to the surface (Cretney *et al.* 2002). In the reverse process, northward winds force surface water toward the coast, producing an increase in sea level and downwelling currents. Winter storm winds that bring rain also push surface waters of Hecate Strait into the mainland channels. In addition, water from heavy rains of late autumn and winter discharge into the same channels and then into Hecate Strait, where they form buoyancy currents. Cretney *et al.* (2002) state that the variability in upwelling, particularly at the time of the spring transition, is not known in detail. Yet these are crucial features influencing total plankton and fish productivity.

2.1.5 Sea-level Changes

The Prince Rupert sea level record, spanning 90 years of nearly continuous observations, reveals a rising trend of about 1 mm/year. These sea-level changes are referenced to a benchmark in nearby bedrock, and are therefore *relative* sea-level changes. They are somewhat lower than the *absolute* global sea level rise of 1.5 to 2 mm/year over the past 100 years (IPCC, Climate Change 2001). Even though its impacts in British Columbia are minor at present, Cretney *et al.* (2002) state that global sea level rise associated with any climate warming and associated changes in weather patterns may become a major issue in the future.

2.2 MODELLING NEEDS AND ISSUES

Although several numerical hydrodynamical models have been applied to the Queen Charlotte Basin in the past decade, better numerical techniques and faster computers are continually being developed. With particular regard to oil and gas exploration, Crawford *et al.* (2002a) state that improved simulations of winter currents, tidal currents, bottom currents, rates of exchange between basins, penetration of contaminants into inlets, channels and bays, and the potential for oil to sink below surface brackish water and penetrate into inlets below surface all need to be included in a new suite of circulation models. The complex summer plumes on the east side of Hecate Strait and Queen Charlotte Sound, caused by upwelling and tidal mixing, present unique challenges to the implementation of oceanographic models in the Queen Charlotte Basin (Cretney *et al.* 2002). Winter surface currents are even less known and there are few measurements of the small-scale nearshore winds that force many of these processes. Clearly more observations are required before any model attempting to simulate these features can be deemed credible.

2.2.1 Boundary, initial and forcing conditions

Regional ocean circulation modelling for the Queen Charlotte Basin requires realistic initial conditions and boundary conditions that must include a variety of forcings. Each grid point within the model domain needs to be initialized with realistic values of temperature, salinity and (sometimes) velocity. Accurate lateral boundary conditions that reflect all incoming and outgoing transports also

need to be specified. Boundary forcing can be imposed at both the ocean surface (winds, heat and freshwater exchange), bottom (frictional drag) and along the lateral boundaries (e.g., river discharge). These initial and boundary conditions are usually taken from observations, or from other models. An important consideration for circulation models that are coupled to ecosystem models is their vertical resolution. Correct representation of vertical mixing is important in determining the overall nutrient and carbon fluxes and must be appropriate for biological studies where time and space scales of interest are often shorter and smaller (Fasham *et al.* 1990).

2.2.2 Data for evaluation/validation

Observations are an important part of the modelling process. In fact, some modellers insist that a model is only as good as the data that is used to evaluate it. Hindcast and process study models need to have their results compared with observations in order to confirm the realism of the simulation. This is usually done by point-by-point comparisons over a specific time period, by computing statistics or by extracting characteristic modes and significant parameters. Forecast simulations need to be evaluated in a similar fashion once subsequent observations are available. However, care must be taken to isolate the discrepancies that are due to inaccurate initial conditions or forcing (e.g., weather forecasts), as opposed to those that are due to inaccuracies arising from the simplified model dynamics or numerics. A wide range of data is available for the Queen Charlotte Basin region and a summary is provided in Appendix I.

2.2.3 Previous circulation model applications to Hecate Loma

A survey of previous model applications to this region was given by Crawford (2002a). Here is a brief summary.

Foreman *et al.* (1993) developed a diagnostic, finite element, barotropic tidal model (based on Walters 1992) for the north coast of British Columbia using eight tidal constituents. Constituent accuracy was found to be within 2 cm and 3 degrees for most tide gauges locations. Tidal residual currents calculated by the model suggested the existence of eddies off the tip of Cape St. James, Cape Chacon, and around Goose Island and Learmonth Banks. The shallow water constituents in Hecate Strait were shown to have significant contributions from the constructive interference of signals propagating into Dixon Entrance and Queen Charlotte Sound. Ballantyne *et al.* (1996) extended this model to simulate seasonal buoyancy flows for the north coast where seasonal changes in the Rose Spit Eddy became evident. In her Ph. D. thesis, Jacques (1997) presented a more complete analysis of the application of FEM techniques to the currents in these same waters.

Masson (1996) carried out a field program in the vicinity of Cape St. James, where a strong tidally driven flow interacts with an active surface wave climate. A comparison between drifter and surface currents measured by radar indicated reasonable agreement between the model and the observations. Wave/current refraction effects were found to be important during the first part of the study period and were the likely cause for the phase discrepancy between the measurements and the results of the local model.

Cummins and Oey (1997) used the three-dimensional, prognostic, finite difference, Princeton Ocean Model (POM) to study baroclinic tides in northern British Columbia coastal waters. Experiments with stratified and homogeneous fluid were compared. The barotropic response showed good agreement with previously published studies while internal tides were generated in cases where the model was initialized with a vertical stratification. Observed and modeled M_2 current ellipses were shown to be in good agreement at several moorings and the general significance of the internal tide was demonstrated.

Foreman *et al.* (1998) computed average summer and winter sea surface heights from detided TOPEX/POSEIDON satellite altimetry and extended these fields to the nearshore regions by including concurrent time series from 11 tide gauges. Surface currents were calculated from these seasonal elevation fields using a diagnostic finite element model and then compared with those calculated from historical conductivity and temperature versus depth measurements and those measured by historical near-surface current meters. The large scale features were in reasonable agreement.

Crawford *et al.* (1998a) evaluated the application of the Foreman *et al.* (1993) and Cummins and Oey (1997) models to the QCB and portions of the West Coast of the Queen Charlotte Islands by comparing model simulations of tidal currents to drifter observations for late spring and summer conditions between 1990 and 1995. Generally, the baroclinic model provided better agreement with observations near the shelf break, while the barotropic model was better in regions far inshore of the shelf break. It was proposed that a smaller grid size and better resolution of bottom topography in POM (Princeton Ocean Model) would likely improve the internal tide simulations on the continental shelf and in Dixon Entrance.

Crawford *et al.* (1999a) extended this comparison between drifter-measured currents and two model simulations of surface currents. In this case, the first simulation was a steady state baroclinic calculation (similar to Ballantyne *et al.* 1996) based on historical summer water property measurements, while the second was with POM and actual measured winds. The diagnostic model (FUNDY5) by itself provided a goodness-of-fit of only 3%, whereas POM had a value of 42%. The combination of FUNDY5 plus daily winds improved the fit to 43%. Although the prognostic model performed only as well as the winds by themselves, it simulated the near shore currents more accurately and on average, reproduced the speeds and veering in the surface Ekman layer without bias. Residual currents unexplained by POM were likely due to a combination of advection of water masses into this region (i.e., inadequate boundary conditions), horizontal inhomogeneities in the density field (inadequate initial conditions), Stokes drift of wind waves, and net Lagrangian tidal motion not represented by the model.

Foreman *et al.* (2000) developed a high resolution, nonlinear, barotropic, finite element tidal model for removing tidal elevations from satellite altimeter observations (Cherniawsky *et al.* 2001) throughout the northeast Pacific Ocean, north of 30°N and east of the dateline. The model was able to simulate the full tidal signal to an accuracy of approximately 5 cm.

Di Lorenzo *et al.* (2005) used the Regional Ocean Modeling System (ROMS) to demonstrate that Haida Eddies are typically generated each winter by buoyant water flowing southward past the east side of Cape St. James. The model was forced with average annual cycles of climatological winds, surface heat flux, and temperature and salinity along the open boundaries. Annual cycles of sea surface elevation measured at coastal tide gauges and TOPEX/POSEIDON crossover locations were reproduced with reasonable accuracy. As suggested by previous in-situ water property measurements, these experiments showed that the eddies are generally comprised of mixed layer water from Hecate Strait, Queen Charlotte Sound, and the continental shelves off northern Vancouver Island. Consistent with satellite altimeter observations (Crawford *et al.* 2002c), small eddies were seen to form initially to the west of the cape and then, as their size increased, detach from the coast and drift westward. Newly formed eddies often merged with an existing larger eddy soon after they detached. Mature Haida Eddies were approximately 200km in diameter and had vertical extents of roughly 1000 m. An accurate representation of bathymetry was found to be important for the realistic simulation of the generation and shedding processes.

Whitney *et al.* (2002) suggested that Haida Eddies play a significant role in transferring nutrients and larvae from Hecate Strait to the ambient ocean. A major challenge for future modeling studies will be to predict the generation and evolution of these eddies so that better estimates of productivity and recruitment can be provided to ecosystem managers.

The Canadian Search and Rescue Planning (CANSARP- Search & Rescue tracking tool) computer program was developed to improve the effectiveness of Search and Rescue (SAR) operations of the Canadian Coast Guard (CCG). CANSARP is a mathematical model that accepts current and wind data to predict the drift of rescue targets, so that searches can be directed toward the appropriate location. Presently, drift predictions are based mainly on current patterns derived from historical data and modelled barotropic tides. CANSARP is the primary drift and search planning tool for all BC coastal and offshore waters. Input data includes direct real-time weather from Environment Canada, existing ocean and tidal current database predictions, real-time total water currents from deployed drift buoys (deployed as required) and weather and current data received from vessels and aircraft on scene (Jeff Nemarava, Supervisor SAR Program, CCG Pacific, pers comm.).

The AES wind acquisition programs and scripts automate the collection of wind data from the Canadian Meteorological Centre (CMC) in Dorval. Each RCC (Rescue Coordination Centre) and MRSC (Marine Rescue Sub-Centre) connects to CMC once every 6 hours to down-load the latest wind observations and model analysis/forecast for its Search and Rescue Region (SRR). Through this link, CANSARP possesses the latest 48 hour forecast as well as an indefinite record of observed and model analyzed winds in memory. With this capability, a high resolution wind field, especially in or near shipping lanes, is ready to be accessed with the push of a button. Experience to date has proven that these wind fields result in smaller, better defined search areas.

2.2.4 Modelling oil spills

The Report of the Expert Panel on Science Issues Related to Oil and Gas Activities, Offshore British Columbia, 2004 (Executive summary) recommended that in order to assess biological and ecological impacts, oil spill trajectory modeling should be carried out for a wide range of oil types, spill locations, and weather and sea conditions. It also stated that the probability distributions of wind velocity, wave height, and current velocity need to be known, so that the response of a structure under normal operating conditions, the possible failures due to fatigue, and the possible downtime due to weather, can all be assessed. In addition, the physical and particularly, toxicological impact of discharges of drilling waste (mud, cuttings) and produced water should be taken into consideration (Strong *et al.* 2002). Crawford *et al.* (2002a) described the fate of oil, produced water and drilling muds that may be introduced into the ocean by offshore oil exploration and production, and also discussed models for these fates. Hodgins (1992) evaluated spill predictions at Cape St. James and found that the surface current simulations disagreed with the actual observed currents. Thus the impact of oil spills on this region could not be determined by hydrodynamical models as they existed at that time (Crawford *et al.* 2002a).

Crawford *et al.* (2002a) stated that models of contaminant fates must be implemented for the Queen Charlotte Basin. In winter, prevailing winds and storm systems will undoubtedly transport spilled oil onto shores and penetrate certain beaches in the intertidal zone with consequent increased environmental impact. There are also areas near the Queen Charlotte Islands where wave and current refraction are significant. Numerical refraction models can be used to calculate these effects. Crawford *et al. (*2002a) recommended that modelling should be carried out for specific oil and gas activities in order to establish coastal zone buffers of sufficient size that oil spill response could be activated before oil from a spill made landfall.

Crawford *et al.* (2002a) also stated that the long-term fate of spilled oil is affected by several processes with evaporation, dispersion and emulsification (water-in-oil) being the most important. Processes such as drift, emulsification, and shoreline adhesion require knowledge of shoreline slope and material, ocean currents, tidal currents, wind and wave regimes, usually at each site in the basin, and at each season of the year.

As identified by Crawford *et al.* (2002a), several important features have thus far not been included in current oil spill fate and effect models. Some of these are:

- Current oil-spill models do not handle strong surface gradients well (Spaulding 1995; ASCE Task Committee 1996; Reed *et al.* 1999)
- Present oil spill fate and effect models do not take into account the interaction of oil droplets and suspended particulate matter.
- Photo-oxidation, a process which occurs when sunlight and oxygen react with oil under the right conditions and which leads to the breakdown of complex compounds to compounds that are lighter in weight and more water soluble, is not included in most oil spill models.
- Biodegradation process models do not seem to be under development for inclusion in oil spill fate and effects models.
- Oil-shoreline interaction models still need to better describe the physicochemical processes involved in remobilization of oil from a beach face during and after the oiling event (Reed *et al.* 1999).
- As yet, integrated oil spill behaviour models do not encompass Langmuir circulation and other small scale near-surface oceanographic processes.

3.0 DESCRIPTION OF CANDIDATE CIRCULATION MODELS

3.1 PRINCETON OCEAN MODEL – POM

The following was copied from the Princeton University POM website in March 2005 with some additional information from the June 2004 POM Users' guide (Mellor 2004).

The Princeton Ocean Model (POM) is a sigma coordinate, free surface, ocean model, which includes a turbulence sub-model. It was developed in the late 1970's by Blumberg and Mellor, with subsequent contributions from several other people. The model has been used for modeling of estuaries, coastal regions, basin and global oceans. Support has been provided by ONR, NOAA, MMS and other agencies.

The principal attributes of the model are as follows:

- It contains an imbedded second moment turbulence closure sub-model to provide vertical mixing coefficients.
- It employs a sigma coordinate or a terrain-following transformation in the vertical to provide a continuous representation of changing bathymetry.
- The horizontal grid uses curvilinear orthogonal or Cartesian coordinates and an "Arakawa C" differencing scheme.
- The horizontal time differencing is explicit whereas the vertical differencing is implicit. The latter eliminates time constraints for the vertical coordinate and permits the use of fine vertical resolution in the surface and bottom boundary layers.
- The model has a free surface and a split time step. The external mode portion of the model is two-dimensional and uses a short time step based on the CFL stability

condition and the external wave speed. The internal mode is three-dimensional and uses a long time step based on the CFL condition and the internal wave speed.

- Complete thermodynamics have been implemented.

The turbulence closure sub-model was introduced by Mellor (1973) and then significantly advanced in collaboration with Yamada (Mellor and Yamada 1974; Mellor and Yamada 1982). Though often cited in the literature as the Mellor-Yamada turbulence closure model, it is based on extending the turbulence hypotheses by Rotta and Kolmogorov stratified flow cases. The level 2.5 turbulence model is used together with a prognostic equation for the turbulence macroscale.

The sigma coordinate system is probably a necessary attribute in dealing with significant topographical variability such as that encountered in estuaries or over continental shelf breaks and slopes. Together with the turbulence sub-model, the model produces realistic bottom boundary layers which are important in coastal waters (Mellor 1985) and in tidally driven estuaries (Oey *et al.* 1985a, b).

The program that is now supplied to outside users includes a test that simulates the east-west flow across a seamount with a prescribed vertical temperature stratification, constant salinity, zero surface heat and salinity flux, and a zero wind stress (though wind stress may be easily applied). The program should run with no additional data requirements.

The Princeton Ocean Model (POM) is well-tested and widely-used. It has been applied extensively at IOS and elsewhere and has a good downloadable manual. It has been used for modelling estuaries, coastal regions, basins and global oceans. Though a curvilinear coordinate system exists, it is intended for more gentle coastal changes than are found off northern BC. Thus one limitation of the method (in fact, this is a limitation of all finite difference methods) concerns the coarse staircase-like approximation that would arise when trying to represent the complex network of islands, channels, and fiords found along the central and northern mainland coast of British Columbia. In order to capture these features, a very high resolution or nested grid which places more demands on computational resources would be required. Applications at IOS have utilized only Cartesian co-ordinate grids as they are simple and appropriate for limited area domains. Though the lack of a wetting-and-drying capability is another possible limitation of POM, it should not be a factor in northern BC waters where there are not significant mudflats.

There are several publications by IOS scientists who have used POM:

Cummins, P.F. and Oey, L.Y. 1997. Simulation of barotropic and baroclinic tides off northern British Columbia. J. Phys. Oceanog. 27: 762-781.

Crawford, W.R., Cherniawsky, J.Y., Cummins, P.F. and Foreman, M.G.G. 1998a. Variability of tidal currents in a wide strait: A comparison between drifter observation and numerical simulations. J. Geophys. Res. 103: 12,743-12,759.

Crawford W.R., Cherniawsky, J.Y. and Cummins, P.F. 1999a. Surface currents in British Columbia waters: Comparison of observations and model predictions. Atmosphere-Ocean. 37: 255-280.

Cummins, P.F., Cherniawsky, J.Y. and Foreman, M.G.G. 2001. Internal tide generation along the Aleutian Ridge. Journal of Marine Research. 59(2): 167-191.

Masson, D. and Cummins, P.F. 1999. Numerical simulations of a buoyancy-driven coastal countercurrent off Vancouver Island. J. Phys. Oceanogr. 29(3): 418-435.

Masson, D. and Cummins, P.F. 2004. Observations and modeling of seasonal variability in the Straits of Georgia and Juan de Fuca. J. Mar. Res. 62: 491-516.

In addition, Scott Tinis and Richard Thomson use POM operationally to simulate tidal elevations and currents on the West Coast of Canada and Northwest Washington State and to model SST and sea level anomalies in the Northeast Pacific Ocean (http://www.pac.dfo-mpo.gc.ca/sci/juandefuca/default_e.htm).

As of March 2005, POM has 2184 registered users from 71 countries. Below is a partial list of POM users, as stated on the POM website in March 2005:

- *PROFS-Princeton Regional Ocean Forecasting System (GOM)*
- *New York Harbor Observing and Prediction System, NYHOPS (SIT)*
- *U.S. Coastal Observing Systems, COOS (NOAA)*
- *Coast Survey Development Laboratory Forecasting Systems (NOAA/NOS)*
- *U.S. East Coast Coastal Ocean Forecast System, COFS (NCEP)*
- *Southeast Atlantic Coastal Ocean Observing System (Sea-Coos)*
- *GoMOOS- Gulf of Maine Ocean Observing System (UM)*
- *Gulf of Mexico (Dynalysis)*
- *The Great Lakes Forecasting System (GLERL)*
- *Japan Coastal Ocean Predictability Experiment, JCOPE (JAMSTEC)*
- *Intra-America Sea Nowcast/Forecast System, IASNFS (NRL)*
- *Tampa Bay Physical Oceanographic Real-Time System, PORTS (USF)*
- *Adriatic Sea Forecasts (INGV, Italy)*
- *Mediterranean Forecasting System (INGV, Italy)*
- *Cyprus Coastal Ocean Forecasting and Observing System (CYCOFOS)*
- *Ice-Ocean Forecasts for the East Coast of Canada (BIO)*
- *GOTM- General Ocean Turbulence Model (Burchard et al.,)*
- *ECOM-si version of POM (HydroQual) and ECOMSED*
- *MI-POM at the Norwegian Meteorological Institute (A. Melsom)*
- *MEDMEX (Mediterranean Model Evaluation Experiment)*

Here are some other applications of POM to the U.S. Pacific coast:

Gan, J. and Allen, J.S. 2002. *Modeling study of upwelling processes over the Oregon shelf.* EOS Trans. AGU, 83(47). OS62A-0228.

Spitz, Y.H., Gan, J. and Allen, J.S. 2002. *Three-dimensional response of the ecosystem to upwelling off the Oregon Coast.* EOS Trans. AGU, 83(47). OS62A-0240.

Shulman, I. and Rochford, P.A. 2000. *Boundary Conditions in the Pacific West Coast* Princeton Ocean Model of CoBALT. Naval Research Lab Stennis Space Center MS. A499973. Storming Media, Washington, DC. 19 p.

POM has also been used in the Hecate LOMA area. Please refer to *2.2.3 Previous circulation model applications to Hecate Loma* in this report for details.

3.2 EULERIAN-LAGRANGIAN CIRCULATION (ELCIRC) AND SEMI-IMPLICIT EULERIAN-LAGRANGIAN FINIT ELEMENT (SELFE)

The following description of ELCIRC was copied from Center for Coastal and Land-Margin Research (CCALMR) of the OGI School of Science & Engineering at the Oregon Health & Science University CORIE web site in March 2005:

> While developed at OHSU by the CORIE team, ELCIRC is inspired by the work of Vincenzo Casulli, at the University of Trento, Italy. Like Casulli's UNTRIM, ELCIRC is an Eulerian-Lagrangian finite volume model operating on unstructured grids. Both models solve for the 3D baroclinic form of the shallow water equations. ELCIRC is an unstructured-grid model designed for the effective simulation of 3D baroclinic circulation across river-to-ocean scales. It uses a finite-volume/finite-difference Eulerian-Lagrangian algorithm to solve the shallow water equations, written to realistically address a wide range of physical processes and of atmospheric, ocean and river forcings. The numerical algorithm is low-order, but conserves volume and is stable and computationally efficient. It also naturally incorporates wetting and drying of tidal flats. While originally developed to meet specific modeling challenges for the Columbia River, ELCIRC has been extensively tested against standard ocean/coastal benchmarks, and is starting to be applied to estuaries and continental shelves around the world

SELFE is a prognostic finite element method that has more recently been developed by the CORIE team leaders Zhang and Baptista (2004a). Like ELCIRC, its use of an Eulerian-Lagrangian method for the material derivative terms and semi-implicit time stepping for many of the other terms means that it can employ large time steps without comprising accuracy. The major differences between SELFE and ELCIRC are in their horizontal and vertical discretizations. While predominantly constant shape functions consistent with a finite volume formulation are used in the ELCIRC horizontal approximations, linear shape functions in the context of a finite element approach are used in SELFE. In the vertical, ELCIRC employs level surfaces whereas SELFE uses terrain-following sigma or S-coordinate (Song and Haidvogel 1994) surfaces. In addition to these discretization differences, SELFE also offers options in its Lagrangian backtracking that are not available in ELCIRC. For example, a fifth-order Runge-Kutta scheme can be employed instead of a simple Euler solver at the backtracking stage and the triangle splitting approach suggested by Oliveira *et al.* (2000) can be used to reduce numerical diffusion at the interpolation stage. In short, these backtracking options together with higher order elements and terrain-following coordinates in the vertical should make SELFE more accurate than ELCIRC. Preliminary results obtained from applying both approaches to the circulation in the Broughton Archipelago indicate that this is true.

Unlike ROMS and POM, ELCIRC can simulate the wetting and drying of tide flats. The triangular grid allows variable resolution and better fitting of complicated coastlines and high resolution in regions with sharp gradients. A manual is available from the web site. However, testing at IOS suggests that ELCIRC is overly dispersive and not sufficiently accurate away from the coast unless strongly nudged. SELFE is better but continuing tests suggest that it still not as accurate as POM and ROMS in preserving sharp features like fronts, and in generating nonlinear features like eddies.

There are only two publication (another in preparation) from IOS scientists who have used ELCIRC. However there have been presentations describing applications.

> Robinson, C.L.K., **Morrison, J. and Foreman, M.G.G.** 2005. Oceanographic connectivity among marine protected areas on the north coast of British Columbia, Canada. *Canadian Journal of Fisheries and Aquatic Sciences*, 62, 1350-1362, 2005.

Foreman, M.G.G., Stucchi, D., Zhang, Y. and Baptista, A.M. 2005. Estuarine and tidal currents in the Broughton Archipelago. Submitted to Atmosphere-Ocean.

Foreman, M.G.G. 2004c. ELCIRC Applications to British Columbia Waters. ELCIRC Users Group First Annual Meeting. OGI School of Science & Engineering. Portland, Oregon.

Morrison, J., Robinson, C. and **Foreman, M.G.G**. 2004.Tracking Biological Particles Using Elcirc. ELCIRC Users Group First Annual Meeting. OGI School of Science & Engineering. Portland, Oregon.

Foreman, M.G.G., Hickey, B., Trainer, V., MacFadyen A. and Di Lorenzo, E. 2003. Preliminary modelling and observational studies of the Juan de Fuca Eddy. PICES XII Annual Meeting. Seoul, Republic of Korea.

ELCIRC has been subject to extensive benchmarking and has been applied to the description of important Columbia River features and processes. A limited number of researchers have used ELCIRC in other applications, including a coastal eddy, circulation in a semi-enclosed sea (E. Myers, pers comm.) and in a range of estuaries (A. Chawla, pers comms; Myers and Aikman (submitted); and Pinto *et al.* (submitted) (Zhang *et al.* 2004b). Other users include:

- Oregon Health & Science University CORIE project (Coastal Margin Observatory for the Columbia River
- Topics and users from the first users meeting held on June 28 and 29, 2004:
  - *"Internal Tides in the Bab el Mandab Strait"* Ewa Jarosz and Cheryl Ann Blain (NRL, USA)
  - *"Applications of ELCIRC at LNEC: stratification in the Guadiana estuary and tidal propagation in the Obidos lagoon"*, Ligia Pinto, Anabela de Oliveira and Andre Fortunato (LNEC, Portugal)
  - "Simulating Tidal Characteristics in the Chesapeake Bay using ELCIRC and UnTRIM", Harry Wang and Joe Cho (VIMS, USA)
  - *"Using ELCIRC in NOAA's Coastal Storms Initiative"*, Ed Myers (NOAA, USA) *references\elcircmyers.pdf*
  - *"Heat exchange model in ELCIRC"*, Mike Zulauf (OHSU, USA)

The Robinson *et al.* (2005) paper mentioned above is the only application of ELCIRC to the Hecate Loma area.

3.3 REGIONAL OCEAN MODELING SYSTEM - ROMS

The following was copied from the Rutgers University ROMS web site on February 28, 2005:

> The Regional Ocean Model System (ROMS) is a free-surface, hydrostatic, primitive equation ocean model that uses stretched, terrain-following coordinates in the vertical and orthogonal curvilinear coordinates in the horizontal. Initially, it was based on the S-coordinate Rutgers University Model (SCRUM) described by Song and Haidvogel (1994). ROMS was completely rewritten to improve both its numerics and efficiency in single and multi-threaded computer architectures. Currently ROMS does not designate a single model, but a variety of versions developed in an open mode by different institutions. Its features include:

- an architecture designed for efficiency and performance on single- and multi-threaded computer architectures;
- high-order advection schemes;
- accurate pressure gradient algorithms;
- several subgrid-scale parameterizations, e.g. horizontal mixing of momentum and tracers along vertical levels, geopotential (constant depth) surface, or isopycnic (constant density) surfaces;
- both local and non local closure schemes for the vertical mixing parameterization, with the former based on level 2.5 turbulent kinetic energy equations and the latter on the K-profile, boundary layer formulation;
- atmospheric, oceanic and benthic boundary layers;
- biological modules; radiation boundary conditions;
- data assimilation via either a multivariate, intermittent optimal interpolation (OI) scheme or via error subspace statistical estimation (ESSE);
- a split-explicit time-stepping scheme to separately advance the free-surface and vertically integrated momentum equations for the barotropic and baroclinic components of the flow;
- time-stepping constraints to exactly maintain both volume conservation and the constancy preservation properties needed for tracer equations;
- a third-order accurate predictor (leap frog) and corrector (Adams-Molton) time-stepping algorithm;
- vertical discretization using stretched terrain-following coordinates; horizontal discretization using boundary fitted, orthogonal curvilinear coordinates on a staggered Arakawa C-grid;

ROMS has extensive pre and post-processing software (mostly in Matlab) for data preparation, analysis, plotting, and visualization. The entire input and output data structure of the model is via NetCDF which facilitates the interchange of data between computers, a user community, and other independent analysis software.

Additional ROMS model features taken from http://marine.rutgers.edu/~wilkin/wip/latte/ include:

- free surface, hydrostatic primitive equations model in terrain-following coordinates
- 3rd-order upstream-biased advection (Shchepetkin and McWilliams 1998)
- pressure gradient and equation of state give reduced s-coordinate truncation error (Shchepetkin and McWilliams 2003)
- split-explicit time-stepping of barotropic and baroclinic modes constrained for conservation of volume and tracer constancy (Shchepetkin and McWilliams 2005)
- radiation open boundary conditions and 1-way embedding in exterior model domains (Marchesiello *et al.* 2001)
- synchronous Lagrangian particle tracking
- vertical turbulence closures: KPP (Large *et al.* 1994) and the Generalized Length Scale scheme of Umlauf, and Burchard, 2003 (http://www.gotm.net) encompassing k-e, k-w and Mellor-Yamada (1982)
- intermittent sub-optimal melding assimilation
- tangent linear and adjoint codes written; 4DVar assimilation in development (Moore *et al.* 2003)
- atmospheric, oceanic, and benthic (wave and current) boundary layers (Styles and Glenn 2000)
- coupled ecosystem (7-component NPZD and EcoSim bio-optics) and sediment transport (USGS Community Model) modules

Though ROMS has similar advantages and disadvantages to POM, it also has more options and is more sophisticated. As a consequence, it is more difficult to use. The data structure lends itself to coupling with biological and sediment transport modules and in fact, two simple biological models are included with the downloadable source code. An adjoint code that will facilitate data assimilation has recently been developed and an automatic two-way nesting capability is now available from the French web-site mentioned below. The Rutgers/UCLA ROMS model uses an "S-coordinate" vertical discretization, which is similar to POM, but with some additional parameters to exert control over the distribution of layers so that each layer need not be a fixed percentage of the water column. There is now a user manual available at the Rutgers website http://marine.rutgers.edu/po/documentation/docs.php and both a user manual and excellent package of pre and post-processing software assembled by former UCLA graduate students available from http://www.brest.ird.fr/Roms_tools/.

So far, there is only one paper from IOS scientists, which used ROMS, in this case to model the generation of Haida eddies (Di Lorenzo *et al.* 2005). There are a few presentations as listed below. Currently, the IOS ROMS users include Mike Foreman, Angelica Pena, Bill Williams, Greig Sutherland (contractor), and Wendy Wiggins (UVic co-op student). But admittedly, their experience is far less than that for the IOS POM community. Peña and Foreman are using ROMS for biophysical modeling of the harmful algal blooms that are generated in the Juan de Fuca Eddy at the entrance of Juan de Fuca Strait. The publications and presentations are as follows:

Di Lorenzo, E., **Foreman, M.G.G. and Crawford, W.R**. 2005. Modeling the Generation of Haida Eddies. Deep Sea Research II. 52: 853-873.

Foreman, M.G.G., Hickey, B., Di Lorenzo, E., MacFadyen, A. and Trainer, V. 2004a. Modeling and Observational Studies of the Juan de Fuca Eddy. Presentation at the AGU Ocean Sciences Meeting. Portland, Oregon.

Foreman, M.G.G., Di Lorenzo, E., Hickey, B. and MacFadyen, A. 2004b. Revisiting the Juan de Fuca Eddy: Modelling and Observational Studies. Presentation at the Canadian Meteorological and Oceanographic Society Annual Meeting. Edmonton, Alberta.

Foreman, M.G.G., Di Lorenzo, E., **Morrison, J**., Li, J.Y., Hickey, B., MacFadyen, A. and Trainer, V. 2004d. Ocean circulation modelling in support of ECOHAB PNW. Presentation at the 11th International Conference on Harmful Algae. Cape Town, SA.

Peña, M. A. and Foreman, M. 2005. Biophysical modeling of the Juan de Fuca Eddy. Presentation at the 9th Canadian Workshop on Harmful Marine Algae, St. John's, Newfoundland.

ROMS users around the world (over 500) have been very successful in running applications ranging from regional to basin and even global simulations. In fact with the possible exception of BC waters, there are a series of ROMS models covering all the shelf and deep waters in the Northeast Pacific with users at Scripps, UCLA, Oregon State University, the University of Washington, the Pacific Marine Environmental Laboratory, the University of Alaska, and the Lamont-Doherty Laboratory of Columbia University. ROMS applications in the Northeast Pacific have produced the following publications and presentations:

Curchitser, E., Haidvogel, D., Hermann, A.Y., Dobbins, E. and T. Powell. 2005. *Multi-scale modeling of the North Pacific Ocean I: Assessment and analysis of simulated basin-scale variability (1996-2003).* Journal of Geophysical Research. In press.

Miller, A.J., Di Lorenzo, E., Neilson, D.J., Kim, H.-J., Capotondi, A., Alexander, M.A., Bograd, S.J., Schwing, F.B., Mendelssohn, R., Hedstrom K. and Musgrave, D. L. 2005. *Interdecadal changes in mesoscale eddy variance in the Gulf of Alaska circulation: Implications for the Steller sea lion decline.* Atmosphere-Ocean. In press.

Curchitser, E., Haidvogel, D., Hermann, A.Y., Dobbins, E. and Powell, T. 2004. *A numerical simulation of large-scale physical events in the North Pacific Ocean during the 1997-2003 period.* PICES XIII Annual Meeting. Hawaii, U.S.A. S9-1993.

Hermann, A.J., Curchitser, E.N., Haidvogel, D.B. and Dobbins, E.L. 2004. *A comparison of remote versus local influence of El Niño on the coastal circulation of the Northeast Pacific.* PICES XIII Annual Meeting. Honolulu, Hawaii, U.S.A.

Hermann, A.J., Haidvogel, D.B., Dobbins, E.L., Hinckley, S., Stabeno, P.J., Musgrave, D. and Hedstrom, K. 2003. *Nested Biophysical Modeling of the Coastal Gulf of Alaska: Inferences from Circulation Results.* Marine Science in the Northeast Pacific, Joint Science Symposium, Anchorage, Alaska.

Hermann, A.J., Haidvogel, D.B., Dobbins, E.L., Hinckley, S. and Stabeno, P.J. 2002. *Interannual variability of SST and cross-shelf transport in the coastal Northeast Pacific.* U.S. GLOBEC NEP-CCS SI Meeting. Corvallis, OR.

Sea-Air-Land Modeling and Observing Network (SALMON): The Coastal Gulf of Alaska Circulation Model (3-km grid) (Musgrave).
The SALMON project in conjunction with the Arctic Region Supercomputing Center is currently utilizing the Regional Ocean Modeling System (ROMS) to simulate ocean weather for the Gulf of Alaska, Prince William Sound and Cook Inlet.
http://halibut.ims.uaf.edu:8000/~salmon/modeling/modeling.html

Other ROMS publications include:

Moore, A.M., Arango, H.G., Miller, A.J., Cornuelle, B.D., Di Lorenzo, E. and Neilson, D.J. 2004. *A Comprehensive Ocean Prediction and Analysis System Based on the Tangent Linear and Adjoint Components of a Regional Ocean Model.* Ocean Modelling. 7: 227-258.

Kurapov, A.S., Allen, J.S., Egbert, G.D., Miller, R.N. and S.Y. Erofeeva. 2004. *Data Assimilation in Shelf Circulation Models.* Office of Naval Research [online report]. http://www.coas.oregonstate.edu/research/po/research/kurapov/overview_2004_Nov.html

Kurapov, A.S., Allen, J.S., Egbert, G.D., Kosro, P.M., Levine, M.D. and Boyd, T. 2002. *Data Assimilative Studies of Coastal Circulation off Oregon.* EOS Trans. AGU, 83(47). OS71F-02.

Allen, J.S. 2002. *Progress on physical circulation and ecosystem modeling in the COAST and WEST programs.* AGU 2002 Fall Meeting, San Francisco, California.

MacCready, P. and Geyer, W.R. 2001a. *Estuarine salt flux through an isohaline surface.* J. Geophys. Res. 106(C6): 11629-11637.

Application of the Regional Ocean Modeling System (ROMS) to Water and Sediment Quality Issues in the Southern California Bight. 2003. Prepared by The Coastal Center of the UCLA Institute of the Environment in collaboration with The Coastal and Marine Geology Program. U.S. Geological Survey.

A more complete ROMS Bibliography is available at
http://marine.rutgers.edu/po/index.php?model=roms&page=papers

ROMS has been used in the Hecate LOMA area. Please refer to *2.2.3 Previous circulation model applications to Hecate Loma* in this report for details.

3.4 OTHER MODELS

Mike Foreman (IOS) is leading the circulation modeling component within the ECOHAB PNW project. The primary models are ROMS, POM, and SELFE with the present grid size for the ROMS application being 3 km. Forcings include winds, tides, surface fluxes, and boundary inflows with the atmospheric conditions coming from a regional MM5 model running at the University of Washington. The circulation model will be coupled to a biological model (developed by Angelica Peña) and will also be used to de-tide ship-mounted ADCP observations.

Foreman *et al.* (2000b) describe the application of QUODDY and its diagnostic counterpart, FUNDY5, (both finite element models developed at Dartmouth College by Lynch and colleagues) to calculating seasonal currents over the western continental margin of Vancouver Island. However QUODDY proved to be insufficiently robust and was abandoned as tool in the ECOHAB project.

3.5 COMPARISONS

The following comparisons were presented during the 2001 ROMS users workshop:

Ezer (2001) and Ezer *et al.* (2002) evaluated the different numerical aspects through a comparison between the Princeton Ocean Model (POM) and the Regional Ocean Modeling System (ROMS). Although both models aim at representing coastal to basin-scale problems with similar horizontal and vertical grids and similar subgrid-scale parameterizations, their numerical algorithms, model configuration and code size are very different. The effects of different time stepping algorithms, different advection schemes and different pressure gradient schemes on numerical errors, the stability of the code and the computational efficiency were demonstrated by sensitivity studies with an idealized channel flow and a steep seamount configuration. Ezer compared the computational efficiency and numerical stability of the two models for a range of different time step choices. For example, he showed that while the simpler Leap-Frog time stepping in POM is more stable for small time steps, the more sophisticated Predictor-Corrector time stepping in ROMS becomes more stable for large time steps. As well, Ezer et *al.* (2002) stated that the new time stepping scheme implemented in ROMS showed promising results in allowing the use of time steps larger than that implied by the common CFL stability condition.

Robertson *et al.* (2001) simulated internal tides using both ROMS and a modified version of POM for two different cases of stratification and topography and the results compared. The two cases include a two-dimensional region over the continental slope in the Weddell Sea and a small three-dimensional region in the southern Weddell Sea. As much as possible, the same input parameters and fields were used for the two models. Both models showed reasonable agreement with existing observations. However, the results also showed significant differences. Robertson *et al.* (2001) state that "First, the internal tides developed much faster with ROMS than with the modified version of POM, ~15

days as compared to ~40 days. The internal tidal fields were also quite different in the major axis of the tidal ellipses, and both the positive and negative rotary amplitudes. Potential causes, such as differences in lateral and vertical mixing, vertical coordinate stretching, etc., were investigated." Robertson *et al.* (2003) state that this comparison of the performance of POM and ROMS for a region in the Weddell Sea, indicated that ROMS was preferable for modeling internal tides in a weakly stratified ocean.

4.0 OIL SPILL MODELLING

4.1 INTRODUCTION

Once introduced into the ocean, oil will have physical, chemical and biological interactions that will alter its properties. In addition, oil spreads to thinner layers as it disperses and this will affect not only the ocean surface but also the bordering coastlines (Committee on Oil in the Sea, 2003). The Royal Society of Canada's Report of the Expert Panel on Science Issues Related to Oil and Gas Activities, Offshore British Columbia (2004) recommended that oil spill trajectory modelling should be carried out for a wide range of oil types and locations in the Queen Charlotte Basin and for different weather and sea conditions. The results of these model runs would provide information about the general patterns of oil dispersal that would be necessary for setting up an oil spill response system. As outlined in Crawford *et al.* (2002a), important processes that should be included in an oil spill model are advection, spreading, evaporation, horizontal and vertical dispersion, dissolution, emulsification, sedimentation, oil-shoreline interactions, photodegradation, and biodegradation.

There are two basic ways in which an oil spill model can be run; either in a coupled or composite mode. The former refers to simultaneously running the oil spill model with an ocean circulation model while the latter refers to providing the oil spill model with circulation variables that have been estimated from observations or previous model calculations.

The ocean circulation component within a coupled model produces the precise input that the oil spill model requires. Coupled models are more complex and usually require a physical oceanographer to deal with the wind and current input to the circulation component. The output from the ocean circulation model needs to match the temporal and spatial scales needed as input by the oil spill model (Crawford *et al.* 2002a). A variety of oil spill models have been coupled with ocean circulation models. Examples are given below and summarized in **Table 1**. Examples of composite ocean circulation-oil spill models are also listed below and summarized in **Table 2**.

Some of the advantages and disadvantages of coupling are:

- Coupled models, *if used properly*, will give more accurate information about the fate of an oil spill
- Coupled models require more information, more validation and are more complex. If used improperly, it is easy to get the wrong results
- Composite models are less prone to error but are not as accurate
- Composite models are easier to use
- Both model forms can require very large computers for their processing.

Oil spill models attempt to describe the important physical and chemical processes that transport and weather the oil on and in the sea. There have been recent advances in the areas of advection, spreading, evaporation, dispersion, emulsification, and interactions with ice and shorelines as well as in understanding the interactions of the various processes involved in weathering and dispersal (Reed *et al.*

1999). There are many software packages available for predicting the integrated fate and effects of oil and gas in the ocean and that number is always increasing. These packages are summarized well in Crawford *et al.* 2002a. An overview is presented here.

4.2 COUPLED OIL SPILL/OCEAN CIRCULATION MODELS

There are several oil spill models which are coupled with an ocean circulation model. Here we present a few examples. The following information is taken from the respective websites (March 2005).

The **OSRI** (Oil Spill Recovery Institute) **PWS-NFS** (Prince William Sound Nowcast/Forecast System) is aiming to develop a predictive capability for estimating the currents and temperature and salinity structure of Prince William Sound in near real-time. It includes three modeling components that can provide nowcasts, forecasts and hindcasts on the oceanographic currents, the atmospheric conditions, and oil spill trajectory and chemical fates and effects. In the next few years, a biological model focused on Pacific herring will be added and work will continue to further verify the models and make more information available to users. A mesoscale atmospheric model which passes wind data to the ocean circulation model (POM) which will in turn pass wind and current predictions to the oil spill model, OSCAR. The oil spill model is not operational but rather run by OSRI staff as needed.

Brovchenko *et al.* (2002) have developed a real-time integrated modeling system for weather, currents, wind and waves coupled with oil slick transport and fate model. The MM5 weather forecasting model is used for operational forecasts and it is coupled with an ocean circulation and sediment transport model **THREETOX**, based on the POM model. These models in turn supply input to **OILTOX** – a 3D model of oil slick transport and fate.

The **MEDSLIK** oil spill model was first developed in 1997 (Lardner *et al.* 1998) as part of the EU LIFE project "Subregional contingency Plan for Preparedness and response to Major Pollution Incidents in the Eastern Mediterranean-Levantine". Its algorithms are based on an earlier version of the OILPOL model (Al Rabeh *et al.* 1995) that was used for oil predictions during the Gulf War in 1991. MEDSLIK is a 3D oil spill model designed to predict the transport, fate and weathering of an oil spill in the Levantine Basin and it has recently been coupled to the Mediterranean Forecasting System Pilot Project (MFSPP) and CYCOFOS Near Real Time (NRT) operational forecasts. The underlying circulation model is POM.

The 3D Oil Drift and Fate Model **(BSH-Dmod) (DRIFT)** operated by DMI Ocean Forecast of Denmark, is coupled to the operational 3D Ocean Circulation Model (BSH-Cmod) developed by the BSH (Bundesamt für Seeschiffahrt und Hydrographie) in Germany. The model calculates oil transport, drift and fate at sea surface and subsurface over the North Sea- Baltic Sea system. The model includes the so-called "weathering processes" of oil spreading, evaporation, dispersion (vertical and horizontal), emulsification (water-in-oil emulsion), dissolution and sedimentation. The Oil Drift and 3D Ocean Circulation Model domains are identical and they are both forced by a wind field from DMI's numerical weather prediction model.

MOHID is a three-dimensional water modelling system, developed by MARETEC (Marine and Environmental Technology Research Center) at Instituto Superior Técnico (IST), Technical University of Lisbon. It includes a hydrodynamic module and a Lagrangian transport module. The oil weathering module (**OWM**) uses the 3D hydrodynamics and 3D Lagrangian transport modules. Oil density and viscosity, and processes such as oil spreading, evaporation,

dispersion, sedimentation, dissolution, emulsification, oil beaching and removal techniques, are included.

MARSAIS (Marine SAR Analysis and Interpretation System) is a project funded by the EU Fifth Framework Programme. The oil transport is estimated by two modules, the circulation module (POM) and the wind generated waves module (WAM). Meteorological forcing is taken from a POSEIDON-ETA limited area model.

Southern California Coastal Ocean Observing System (SCCOOS) uses ROMS to provide seamless current maps extending from the beach to waters offshore. Though not yet fully coupled to an oil spill model, surface currents, waves, and wind fields that have been observed, modeled, and forecasted have been designed to aid oil spill response and prevention and search and rescue operations. Real-time surface currents and trajectories will allow the tracking of spills to aid clean up efforts. Real-time wind and wave fields will assist oil spill response personnel in deploying and managing operational assets (booms, spill response vessels, etc.) Statistical descriptions of circulation, wind, and wave fields can be used for assessing risk to existing and future sites where spills have a high probability of occurring.

The **SALMON** Project Model (Kate Hedstrom, Arctic Region Supercomputing Center (ARSC) and Dave Musgrave, University of Alaska at Fairbanks Institute of Marine Science, Alaska) is another ROMS application, in this case to the Gulf of Alaska. It is not yet fully coupled to an oil spill model but it does simulate transport via numerical Lagrangian drifters and thus could be used for oil spill risk assessment.

4.3 COMPOSITE/INTEGRATED OIL SPILL MODELS

Another approach is to have a composite or integrated oil spill and an ocean circulation model in which both the oil spill fates and effects and the hydrodynamical components are either combined in one model, or the circulation variables are provided as input. Some examples are presented below.

The **VOS** oil spill fate model developed at the Far Eastern Regional Hydrometeorological Research Institute (FERHRI) in Russia uses hydrometeorological sub-models to provide input to the oil spill model.

GNOME (General NOAA Oil Modeling Environment) is a publicly available oil spill trajectory model that simulates oil movement due to winds, currents, tides, and spreading. GNOME was developed by the Hazardous Materials Response Division (HAZMAT) of the National Oceanic and Atmospheric Administration Office of Response and Restoration (NOAA OR&R). However, it is regionally dependent and as of November 2004, the Queen Charlotte Assessment Region did not have a prepackaged location file. Hydrodynamic variables are either input or integrated into the model (Crawford *et al.* 2002a).

SIMAP is an *integrated* Oil Spill Impact Model System developed by Applied Science Associates (ASA) which estimates physical fates and biological effects of releases of oil. Both the physical fates and biological effects models are three dimensional. Current data for the area of interest may be empirical (from direct observations) or calculated by a hydrodynamic model. ASA's hydrodynamic models provide standardized current data sets, which are seamlessly read by the SIMAP physical fates and biological effects models. The user also supplies a wind time series. The models are coupled to a geographic information system (GIS) which contains environmental and biological data,

and also to databases of physical-chemical properties and biological abundance, containing necessary inputs for the models. The cost of **SIMAP** is in the range of US$40K - US$80K.

According to their website March 2005, **SL Ross Environmental Research Ltd (Canada),** a consulting firm specializing in oil spills and their control, have developed an oil spill behaviour model that describes the trajectory and behaviour of marine oil spills as a function of type, size, oil properties and prevailing environmental conditions. The model calculates spreading, evaporation, natural dispersion and emulsification at regular intervals and provides data on the spill's viscosity, density, water content, volume-on-surface, areas, dispersed and evaporated volumes, pour point and thickness. The model is capable of describing the fate and behaviour of oil spills involving waxy, high-pour-point oils, spills of heavy oils that submerge or sink beneath the water surface and spills in broken ice conditions. Water current data is entered or imported to the model in a raster format.

4.4 COMMERCIAL OIL SPILL MODELS

There are many commercial/public models available. Two are presented here.

As stated on their website, **Applied Science Associates' (ASA) OILMAP** is a widely used relative of **SIMAP**. **OILMAP** provides rapid predictions of the movement of spilled oil. It includes simple graphical procedures for entering both wind and hydrodynamic data and specifying the spill scenario. It also includes algorithms for spreading, evaporation, emulsification, entrainment, oil-shoreline interaction, and oil-ice interaction. Some of their other products include **CHEMMAP**, a 3-dimensional chemical discharge model designed to predict the trajectory, fate, impacts and biological effects of a wide variety of chemical substances and **MUDMAP**, a personal computer based model that predicts the transport, dispersion, and seabed deposition of drilling muds and produced water derived from drill cuttings. Though there are variations based on modules selected, typical pricing for OILMAP is in the US$15K - US$25K range. If the user also purchases hydrodynamic models, or linkages to existing models/data, then additional customization may be required.

The Australian Maritime Safety Authority (AMSA) originally interfaced a 3-dimensional continental shelf circulation model, GCOM3D, with **OILMAP**. In June 2004, AMSA purchased **HYDROMAP**, ASA's ocean/coastal model, to predict ocean currents and enable accurate predictions of the water movement in the event of spills near the coast. APASA's (Asia Pacific Applied Science Associates) on-line newsletter states that the **OILMAP-HYDROMAP** system has the ability to include large scale currents measured by orbiting satellites supplied by CSIRO, as well as wind data and forecasts provided by the Bureau of Meteorology. This allows the user to run models forward in time and predict the future movement and weathering of the oil. According to Eoin Howlett (ASA, pers. comm.), similar coupling of a hydrodynamic model and OILMAP is also being carried out by Petrobras in Brazil and the US Navy.

According to SINTEF's website, **OSCAR (Oil Spill Contingency And Response)** is based on their data-based oil weathering model (Aamo *et al.* 1993; Daling *et al.* 1990, 1991), a three-dimensional oil trajectory and chemical fates model (Reed *et al.* 1995b), an oil spill combat model (Aamo *et al.* 1995, 1996), and exposure models for fish and ichthyoplankton (Reed *et al.* 1995a, 1996a), birds, and marine mammals (Downing and Reed 1996). Chemical and toxicological parameters are supplied to the model from oil and chemical databases. Results of model simulations are stored at discrete time-steps in computer files, which are then available as input to one or more biological exposure models. OSCAR includes algorithms to calculate surface spreading, advection, entrainment, emulsification, and volatilisation at the surface and

degradation in water and sediments. Horizontal and vertical advection and dispersion of entrained and dissolved hydrocarbons in the water column are simulated by random walk procedures. At the present time, **OSCAR** does not calculate the interaction of oil with suspended particulate matter and the sedimentation of such material.

OSRI (Oil Spill Recovery Institute) PWS-NFS (Prince William Sound Nowcast/Forecast System) (See Coupled Oil Spill/Ocean Circulation Models above). Staff and other investigators run the **OSCAR** model using data provided by a POM through a web linkage. At the present time, the NC/FC system is receiving real-time data from a single data buoy in PWS, transmitting it to the University of Miami (where the nowcast/forecast hydrodynamic model is run) and then sending the data back to Cordova (Alaska) so that they can be coupled with the **OSCAR** model for making predictive trajectory runs.

4.5 CANADIAN MODELS AND RESOURCES

Oil Spill Response Information System (OSRIS), a computer-based Marine Oil Spill Response Information System, was developed in 1992 by BC Environment, Lands and Parks. OSRIS is now part of the Ministry of Sustainable Resource Management and is one of several of applications using that ministry's extensive Coastal Inventory program. OSRIS and the Coastal Inventory system include satellite images, digital maps and geographically referenced information. The inventory includes more than 50 coastal resources such as the physical character of the shorelines and the biological species that interact with the shoreline, such as fish, birds, and marine mammals. A computer modeling program, which considers such aspects as oil residency, coastal resources present, species rating, seasonality, and human-use rankings, calculates the sensitivity of each shoreline unit. This enables priorities to be set for shoreline protection from oil pollution. During a spill event, OSRIS has a spill trajectory model that can simulate the spread of oil depending on wind direction, time and current/tidal regimes. OSRIS determines the most environmentally sound cleanup strategies for shoreline cleanup.

As stated on their website, the **Centre for Offshore Oil and Gas Environmental Research (COOGER)** was established by Fisheries and Oceans Canada to coordinate the department's nation-wide research into the environmental and oceanographic impacts of offshore petroleum exploration, production and transportation. The Secretariat office of this national research centre is based at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia, and the centre seeks to improve scientific knowledge, identify priority research needs and coordinate and implement collaborative research efforts. Some of its research projects and lead investigators include:

- Field Verification of Benthic Boundary Layer Modelling Effects (Charles Hannah & John Loder)
- Fate and Effects of Chemically Dispersed Oil (Kenneth Lee)
- Monte Carlo Modeling of Oil Aggregates (Kenneth Lee)
- Currents and Circulation in the Atlantic Offshore (John Loder et Guoqi Han)
- Current and Temperature Changes along the Newfoundland and Scotian Shelf Edge (Hannah&Loder)

4.6 DRILLING MUD AND "PRODUCED WATER" MODELLING

4.6.1 Drilling muds

Large quantities of drilling wastes are released into the marine environment during the exploration and extraction of offshore oil and gas from beneath the ocean floor. Drilling muds are a suspension of solids and dissolved materials in a base of water, oil or other synthetic material. Strong tidal currents disperse these materials rapidly. Due to the effect of turbulence, fine grain particles within the

discharge plume collide with each other and form flocs with relatively larger diameters and faster settling speeds. The re-suspended materials are transported away by ocean currents and re-deposited depending on environmental factors (such as water depth, bottom configuration, and energy regime). Smothering of benthic fauna and flora, reduced growth rate and increased mortality are some of the environmental impacts of drilling muds (Niu 2003). Gordon *et al.* (2000) describe the factors that need to be considered when modelling the fate and effects of drilling mud discharges on the marine environment. These are:

- the physical, chemical and biological properties of the drill mud and its components;
- the pathways by which drill mud components move in the environment;
- the partitioning of the drill mud between the different pathways;
- the dose-response of the organisms of interest to the drill mud components and
- the physical and biological environment receiving the discharges (Crawford *et al.* 2002a).

DFO has initiated a multidisciplinary research program to study the environmental pathways, transport rate, and ultimate fate and effects of drilling and production wastes. A quantitative description of the physical environment has been included to determine the potential trajectories and dispersion of drilling wastes. A comprehensive three-dimensional circulation model of the eastern Canadian continental shelf has been developed using data from current moorings. A benthic boundary layer transport (BBLT) model has been developed by DFO, Maritimes region, to predict the transport and dispersion of suspended particulate drill waste (primarily barite and bentonite) on the continental shelf (Hannah *et al.* 1995, 1996, 1998; Boudreau *et al.* 1999 and Gordon *et al.* 2000). Model predictions in conjunction with results of biological/chemical studies have been used to assess the risk of environmental impacts resulting from offshore oil/gas developments. The model now includes a continental shelf sediment transport model developed by the Geological Survey of Canada Atlantic (GSCA) and this has improved predictions of the effects of both currents and waves on the fate of drilling wastes. A simple model of flocculation and break-up processes has recently been added (Cranford *et al.* 2001). A spatially-variable version of the BBLT model, using current and stress fields from the 3-d finite-element hydrodynamics model, is being developed (Xu *et al.* 2000a).

4.6.2 Produced water

Produced water is defined as the water extracted from the subsurface with oil and gas. It may include water from the reservoir, water that has been injected into the formation and any chemicals added during the production/treatment process. Produced water is also called "brine" (and may contain high mineral or salt content) or "formation water".

More than 90% of the inputs into the marine environment from extraction activities are from produced water discharges, which release low but continuous amounts of dissolved components and dispersed crude oil (Utvik 1999). Elevated levels of contaminants in sediments from produced water can extend up to 300 m from the discharge point. Produced water is the largest volume waste stream from oil and gas production activities (Committee on Oil in the Sea: 2003). Vavrek *et al.* (2004) reviewed 551 publications relating to remediation of oilfield brine spill sites and determined that there was a lack of information. Here we present some current produced water models.

i) DREAM (Dose-related Risk and Effect Assessment Model) has been developed by a group of Norwegian companies to assess acute and chronic risks associated with long term, low-level releases to the marine environment. It is derived from PROVANN (Reed *et al.* 1996b) and CHARM (Chemical Hazard Assessment and Risk Management). The discrete components of DREAM are as follows:

- time-space variations of discharge concentration fields;

- exposure of organisms with different behaviour patterns;
- assessment of mixtures of chemicals;
- assessment of sub-lethal chronic effects

DREAM links these processes together within a unified model system, including databases (Crawford *et al.* 2002a).

ii) PROTEUS (Pollution Risk Offshore Technical EvalUation System), as stated on their website, developed by BMT (British Maritime Technology) Cordah Ltd., predicts the physical dispersion, chemical interactions and ecotoxicological risk for discharges during all phases of petroleum projects. PROTEUS has been developed over a five year period, during which time academic research into water plume and particulate mixing behaviour, offshore chemical behaviour and marine ecotoxicology has focused on developing the models required to predict the overall impact of discharges. PROTEUS is widely used within the European oil industry. Sabeur *et al.* (2003) describes the numerical development, experimental validation and application of the production discharges module within the PROTEUS system.

iii) Combined Drilling Muds and Produced Water Model

According to ASA's website, **MUDMAP,** developed by Applied Science Associates (ASA), is a personal computer based model that predicts the transport, dispersion, and seabed deposition of drilling muds and produced water derived from drill cuttings. MUDMAP includes detailed models that account for the three stages of movement:

- the free fall of the consolidated mass of mud and cuttings (i.e., convective descent phase)
- the collapse of the consolidated mass as it hits the seafloor (i.e., dynamic collapse phase)
- the subsequent diffusion and deposition of the mud and individual cuttings.

5.0 BIOLOGICAL/ECOSYSTEM MODELLING

5.1 INTRODUCTION

A comprehensive ecosystem model needs to include the physical, chemical and biological processes of the ocean that determine abundance, distribution and productivity of the organisms. Hofmann *et al.* (2002) state that circulation models need to be developed specifically for interdisciplinary studies because circulation models are often limited by their inadequate vertical resolution in the upper 100m of the ocean where most biological processes take place and should also include the dynamics of the mixed layer where processes controlling biological production occur. Large-scale advective flow and high-frequency events such as internal gravity waves that are important to biological production also need to be included. Another important consideration is the parameterization of biological processes.

Hofmann (1998) gives an overview of predictive modeling for marine ecosystems and reviews existing interdisciplinary models for marine ecosystems to assess their strong and weak points and to use this as a basis for directing future research. Several marine ecosystems are discussed in this article and many of the shortfalls of the models discussed are attributed to data limitations, scale differences between the circulation and ecological models, and model structure and parameterization. Some approaches suggested for the improvement of marine ecosystem models are the development of integrated sampling systems, concurrent measurement of physical and biological properties, the development of data assimilation techniques, and advances in model construction.

The most environmentally toxic of the hydrocarbon compounds common in petroleum are the polycyclic aromatic (multiple-ring) hydrocarbons (PAH, also called polynuclear aromatic hydrocarbons, PNA). "Bioavailability", the dose of petroleum hydrocarbons available to an organism, determines the ecotoxicological responses of the specific marine organisms. These processes of bioavailability are some the most complex and least understood aspects of the effects of oil spills and predicting their impact is currently not possible (Committee on Oil in the Sea: 2003).

5.2 PREVIOUS APPLICATIONS TO HECATE (OR ELSEWHERE) AND SUCCESS

Here are some current applications of biological-physical modeling. Examples were chosen to address general issues or to have some relevance to oil spill dispersal issues in the Hecate LOMA.

Foreman *et al.* (2000) applied the finite element model QUODDY4 to simulate summer currents along the southwestern continental margin of Vancouver Island. Historical CTD and wind observations are used to construct initial conditions and forcing fields, and the four largest tidal constituents are included in the simulations to correctly represent mixing and bottom friction. The resultant model currents compared favourably with observations, accurately capturing strong shears both vertically in Juan de Fuca Strait, and horizontally and vertically across the continental shelf and slope. The software package DROG3D was then used to simulate biological transport onto and around the shelf. Major nutrient supply routes were investigated and conform with previous observational studies. An interesting interaction between organisms with diel vertical migration behaviour and the relatively strong K_1 and P_1 tidal currents in the region was shown to exist (Smith *et al.*, 2001).

Denman *et al.* (1999) simulated a simple Fe control on phytoplankton at Ocean Station Papa (OSP) in the subarctic North Pacific with a coupled 1-d mixed layer/four-compartment (Nutrients-Phytoplankton-Zooplankton-Detritus, NPZD) ecosystem model. The best simulations with Fe limitation agreed with observations of the annual cycle of surface nitrate concentration, the *f*-ratio, particulate nitrogen concentration in the euphotic layer, the export production, and the remineralization depth scale of sinking detritus, to within ~50%, probably within the range of observational uncertainty and/or seasonal and interannual variability. They feel that several extensions to their model should improve its simultaneous agreement with different types of observations: (i) increasing the particle sinking speed and/or decreasing the remineralization rate with depth; (ii) dividing the detritus compartment into (a) non-sinking particles and dissolved organic matter, and (b) sinking particles; and (iii) estimating possible horizontal fluxes of nitrate in the surface layer or embedding the model in an ocean general circulation model with horizontal advective terms.

Peña (2003) developed a 1-dimensional plankton ecosystem model with two size classes of phytoplankton and zooplankton for the NE subarctic Pacific to investigate variations in the export of organic particles to the ocean interior due to potential changes in the environment. Results indicated that the relative abundance of small and large phytoplankton changes as the environment changed. Thus, although models with a single phytoplankton component can successfully simulate observations at OSP, their response is limited when employed in predicting responses to changes in the environment since they do not capture potential changes in food web structure.

Haigh et al. (2001) embedded a NPZD plankton ecosystem model to the Miami Isopycnic-Coordinate Ocean Model (MICOM) to investigate the hypothesis that the 1976 "regime shift" in the North Pacific fish population resulted from climatic change propagating up the fisheries food web. Their baseline run with forcing for the period 1952-1988 reasonably reproduces the spatial patterns of seasonal changes in satellite chlorophyll images. Estimates of annual production and export production compare well with contemporary observations of primary and export production at OSP but are low by a factor of 8-10 at station ALOHA near Hawaii.

Olascoaga *et al.* (2005) coupled a NPZD biological model to the MICOM model to study plankton dynamics in the Arabian Sea. Over the course of a year, the NPZD-MICOM coupled model reproduced the seasonal patterns observed in the region, in particular, a pronounced response in the biology of Oman compared to Somalia. As well, the model reproduced blooms of the northeast coast of Oman during the North East Monsoon through convective mixing, offshore and intermonsoon oligotrophic conditions and the offshore deep chlorophyll maximum. Olascoaga *et al.* (2005) state that the model results are in agreement with (the scarce) in situ and satellite data in terms of reproducing temporal and spatial variability in nutrients, phytoplankton and zooplankton concentrations at least qualitatively.

Kishi *et al.* (2003) compared the simulation of particle fluxes using NEMURO and other models in the western North Pacific. The NEMURO model (North Pacific Ecosystem Model Understanding Regional Oceanography) consists of eleven compartments and more than 70 parameter values and was developed, through a series of workshops, by the North Pacific Marine Science Organization (PICES) to simulate the lower trophic ecosystem in the North Pacific Ocean. The NEMURO ecosystem model is compared with several other lower trophic level models of the northern North Pacific: the Kishi and Nakata Model (Kishi *et al.* 1981), the KKYS (Kawamiya *et al.* 1995, 2000a, 2000b), and the Denman model (Denman and Peña 2002). The different ecosystem models are embedded in a common three-dimensional physical model, and the simulated vertical flux of POM (Particulate Organic Matter) and the biomass of phytoplankton are compared. The conclusions were that if the parameters are properly defined: 1) primary production can be well reproduced by all four models, 2) it is difficult to describe the production of POM with simple NPZD models, 3) NEMURO simulated satisfactorily the vertical flux of POM in the northern North Pacific.

Megrey *et al.* (2003) coupled NEMURO with a fish bioenergetic model of individual fish, NEMURO.FISH (NEMURO.For Including Saury and Herring), to explore the impacts of climate change on marine ecosystems as well as the effects of climate change up the marine food-web to fishes. Ito et al. (2004) applied NEMURO.FISH to Pacific saury simulating reasonalble growth rates for that specie. They found that warming in the Kuroshio-Oyashio interfrontal zone decreased the density of prey (zooplankton) and slowed the growth of Pacific saury.

Hermann *et al.* (2001) linked three models for the western Gulf of Alaska: 1) a three-dimensional, eddy-resolving, wind- and runoff-driven circulation model, 2) a probabilistic IBM of growth and mortality for egg and larval stages of walleye pollock (*Theragra chalcogramma*), and 3) an Eulerian, stage-structured NPZ model which includes production of larval pollock prey items. They concluded that it was feasible and efficient to store model velocity and scalar fields, for later use by Lagrangian biological models, it is both feasible and efficient using presently available computers and that the results are reasonably accurate given a sufficiently small time step for spatial tracking. It was also found that boundary conditions for Eulerian prey models should benefit from a careful use of data assimilation, when field data are available.

Cox *et al.* (2003) report on the PWSNF (Prince William Sound Nowcast-Forecast) workshop and the PWS Biological Modeling Workshop which took place in Anchorage, Alaska, 2003 as part of the planning process for Phase II of PWSNF spanning the fiscal years 2004 – 2006 which was hosted by the Oil Spill Recovery Institute. One of the goals of these workshops was to examine means for incorporating biological modeling within PWSNF. The Prince William Sound (PWS) Biological Modeling Workshop in 2003 addressed this issue and came up with some ideas such as definitive conceptual model of the biology of Prince William Sound upon which to build a biological modeling strategy. As noted above, the decision was made to focus on modeling the biology of Pacific herring as it was well enough understood to permit this as well as being one of the most important commercial and

subsistence resources in the region and a key forage resource for a host of fishes, birds and mammals in the Sound. A schematic of the PWS model is presented in **Appendix 2.**

5.3 COUPLED MODELS USING THE PRINCETON OCEAN MODEL (POM)

There are several applications of coupled biological/physical models using POM. We present a few here.

The following was copied from the University of Maine Darling Marine Center website (March 2005).

> This project (a coupled Physical-Biological Model for the Gulf of Maine) carries out simultaneous prognostic integration of a three-dimensional circulation model coupled with a seven-component biological model. It considers the interaction of the important physical, chemical, and biological factors that control biological productivity in the Gulf of Maine. It also enables quantitative measures of the physical and biological coupling in the Gulf, reflected in the nutrient budget of the euphotic zone. We attempt to use the modeled annual nutrient budget, including estimates of atmospheric inputs, to reconcile the previously reported mismatch between nutrient flux to the euphotic zone and primary production in the Gulf of Maine (Schlitz and Cohen 1984; Townsend 1991). We expect this research to result in new insights into the rates of primary production in the Gulf as they vary seasonally and spatially in response to nutrient dynamics. Furthermore, the prognostic ecosystem model can be used to evaluate the sensitivity of the Gulf of Maine ecosystem to various natural and anthropogenic variations in the forcing functions. Beginning at the end of the third year, a 10-component biological model is integrated synchronously with the circulation model for 18 month. Results from the last 12 months are analyzed for seasonal variations in nutrient and plankton distributions.

Baird *et al.* (2004) coupled a five component pelagic ecosystem model to a two dimensional configuration of the Princeton Ocean Model (POM) that represents an idealised ocean basin with upwelling and downwelling regions using empirical descriptions of biological processes that are mathematically similar to those in existing process-based models. Physical processes at the scale of individual planktonic cells that are determining the rates of biological processes are examined in these simulations.

As stated on their website (March 2005), the Marine Ecosystem Dynamics Modeling Laboratory at School of Marine Science and Technology, University of Massachusetts-Dartmouth have coupled a lower trophic level biological model into a full three-dimensional hydrodynamic model (a modified version of Princeton Ocean Model-POM) with application to Lake Michigan.

MFSTEP (Mediterranean Forecasting System Pilot Project) of the MFSPP (Mediterranean Forecasting System Towards Environmental Predictions) are coupling the Mediterranean Sea OGCM (Ocean General Circulation Model) and two of the regional circulation models that they have developed with the BFM (Biochemical Flux Model). According to their website (March 2005), the regional coupled models will obtain (in a one-way, off-line mode) their open boundary conditions from the OGCM model through a nesting procedure. The OGCM covers the entire Mediterranean Sea, while the two regional models cover the Adriatic Sea and the Aegean-Levantine area (the so-called ALERMO area). The two regional models use the Princeton Ocean Model POM.

Fiechter *et al.* (2004) have developed a high-resolution coastal ocean circulation model (EFS-POM, within the Southeast Atlantic Coastal Ocean Observing System (SEACOOS) program) to investigate Florida Current frontal eddies as mechanisms for increased productivity from local

upwelling, cross-shelf water exchanges, and aggregations of biological organisms. Both Eulerian and Lagrangian approaches were used and compared to investigate biophysical transport. Combined with observations, coastal ocean model output is expected to improve the understanding the variability of fish distribution as it relates to mesoscale ocean circulation.

5.4 COUPLED MODELS USING THE REGIONAL OCEAN MODEL SYSTEM (ROMS)

This information was copied from the biogeochemistry group's (Institute of Geophysics and Planetary Physics) UCLA website, http://www.atmos.ucla.edu/cesr/ROMS_page.html, (March 2005).

> The biogeochemistry group (Institute of Geophysics and Planetary Physics, UCLA) are using ROMS, a multi-purpose, multi-disciplinary oceanic modeling tool to investigate the biogeochemical cycling and ecosystem population dynamics along the U.S. West Coast. They have presently incorporated a Nutrient-Phytoplankton-Detritus-Zooplankton (NPDZ) type model into ROMS, including an extension to represent carbon and oxygen cycling. The modularity of the ROMS code makes it possible to configure and explore different ecosystem model formulations, (Fasham *et al.* 1990; Frost 1993; Moisan and Hofmann 1996). ROMS' K-Profile PBL surface boundary layer parameterization scheme (KPP) and its tolerance for highly stretched vertical grids (due to the vertical-spline discretization) makes it particularly suitable for coupled physical-biological modeling to efficiently enhance the resolution near the surface where most of the biological activity takes place.

Dobbins *et al.* (2004) have implemented the Regional Ocean Model System **(ROMS)** with a 3 km grid of the coastal Gulf of Alaska (CGOA), to examine the hypothesis that high productivity is generated by mixing over the bank, which pumps nutrients up from the troughs on either side, feeding phytoplankton over the bank. Included in this model are tidal forcing and daily atmospheric forcing the MM5 atmospheric model. An NPZ model, adapted to the CGOA, is used to generate chlorophyll and nutrient fields. Results indicate that springtime productivity is dominated by the effects of atmospheric events, whereas summer productivity is clearly related to tidal mixing for 2001.

Hermann *et al.* (2003), as part of Northeast Pacific GLOBEC, have developed a set of one-way nested physical and biological models of coastal dynamics, designed to include basin-scale, regional and local influences on coastal transport, and their subsequent impact on lower trophic level dynamics (and ultimately salmon life histories). ROMS is used as the physical model.

Peña and Foreman are using ROMS for biophysical modeling of the harmful algal blooms that are generated in the Juan de Fuca Eddy at the entrance of Juan de Fuca Strait. The NPZD type model being developed includes multiple nutrient limitation and two-sizes of phytoplankton and zooplankton

5.5 OTHER COUPLED BIO-PHYSICAL MODELS

There are also examples of other circulation models used in coupled bio-physical models:

- Alexeeva *et al.* (2003) have developed a coupled bio-physical model based on the HAMSOM (Hamburg Shelf Ocean Model) hydrodynamics. The eco-system block of the coupled model has the number of 11 state variables.

- Stratford *et al.* (2002) developed a fully coupled high resolution ocean general circulation and nutrient cycling model to study the input of Aegean deep water in to the Mediterranean , often referred to as the eastern Mediterranean transient (EMT). The physical model is based on the Geophysical Fluid Dynamics Laboratory Modular Ocean Model (GFDL) with a free surface adapted to the Mediterranean Sea.

- Stipa *et al.* (2003) of the Finnish Institute of Marine Research have developed a coupled physical, chemical and ecological 3-dimensional ocean model composed of separate modules such that the chemical-ecological model is embedded into the physical model equations as reactive, dynamically passive tracers, which are advected and diffused in each time step of the physical model. Both models are integrated numerically simultaneously. The physical model is based on the MIT general circulation model (MIT GCM) (Marshall *et al.* 1997) realised for the Baltic Sea

- Hood *et al.* (2003) use a coupled biological/physical model to synthesize and understand observations taken during the US JGOFS Arabian Sea Process Study (ASPS). Its physical component is a variable-density, 4 -layer model modified from McCreary *et al.* (2001); its biological component consists of a set of advective–diffusive equations in each layer that determine nitrogen concentrations in four compartments, namely, nutrients, phytoplankton, zooplankton, and detritus.

- Wang *et al.* (2002) developed a 3-D coupled biological-physical model of Prince William Sound (PWS) to simulate the spring plankton bloom as part of the *Exxon Valdez* Oil Spill Restoration project. The physical model was based on an existing 3-D circulation model developed from the SEA (Sound Ecosystem Assessment) project and the biological model consists of four compartments: 1) (dissolved organic nitrogen +nitrite) DIN, 2) (phytoplankton) P, 3) (zooplankton) Z, and 4) (detritus) D. Vertical mixing caused by wind stirring and surface cooling is calculated by a mixed-layer model. The model simulated the 1996 spring plankton bloom.

- According to their website (March 2005), a special session on Integrated Biological- Physical Modeling was held as part of IMEMS 2004 (International Marine Environmental Modelling Seminar) which focused on the Louisiana-Texas (LATEX) continental shelf in the Gulf of Mexico, an ecologically heterogeneous, productive marine ecosystem with highly rich fisheries. This is also a site of intense oil and gas activity, whose effects to the ecosystem need to be known and predicted. The Minerals Management Service (MMS USA) is interested in developing an integrated model of this shelf and convened a special session to review the state-of-the-art in biological-physical integration modeling, current practices, and model-data comparison in this field with a view to producing recommendations in designing a pilot study linking data and models. As a first step, coupling of hydrodynamic models to both sediment transport and benthic-pelagic biogeochemical models could be considered.

5.6 DESIRABLE BIOLOGICAL COMPONENTS

The type of biological model developed for the Hecate LOMA would depend on what the desired output would be. It would also depend on what data is available to develop and verify whatever model is implemented. One of the main limitations of ecosystem models is the difficulty of obtaining the necessary observations to guide and validate models. Assigning values to biological parameters is particularly difficult because some parameters do not correspond directly to quantities derived from observations and, even when they do, they are generally difficult to measure and cannot be regarded as constants. Despite these limitations, ecological models are useful tools to understand and quantitatively describe marine ecosystem.

As stated by Hoffman *et al* (1998), "an Eulerian approach establishes the distribution of properties at certain locations in time and thus can provide distributions of passive biological components such as phytoplankton. Lagrangian models tracks particles over time and are used for tracking non-passive biological components such as zooplankton or fish through phytoplankton

distributions. A combined model is useful as long as techniques for interpolating information from the Eulerian grid to the location of the Lagrangian particle are available."

One common type of biological model is the NPZ (Nutrients-Phytoplankton-Zooplankton) or NPZD (Nutrients-Phytoplankton-Zooplankton-Detritus) model. These may include many types of each of the main components as well as many other components which can be included in ecosystem models such as nitrate, ammonium, phosphate, silicate, oxygen, dissolved organic carbon, particulate organic carbon, dissolved organic nitrogen, particulate organic nitrogen, total inorganic nitrogen, exported nitrogen, larval fish, fish and benthos. There can also be multiple size classes or stages of phytoplankton, zooplankton and fish (Hoffman *et al.* 1998).

The resolution of the biological model is often a complex issue due to the different resolutions involved combining physical and biological processes in a single model. Also, available biological measurements are not always readily useable in models except for model verification. What is needed are measurements of the rate at which properties change and how biological processes vary with environmental conditions. The parameterization of biological processes is also important and can dramatically affect the time evolution of the model solution (e.g. Franks *et al.* 1986a; Smith *et al.* 1989; Steele and Henderson 1992, 1995). Representing biological processes using a more process-based approach is also desirable as it would permit development of models that could be valid over a wider range of scales (Hoffman *et al.* 1998).

5.7 COMMERCIAL OIL SPILL FATES AND EFFECTS MODELS WITH BIOLOGICAL COMPONENTS

As previously mentioned in section 4.3 of this report, **SIMAP** is an *integrated* Oil Spill Impact Model System developed by Applied Science Associates (ASA) which estimates physical fates and biological effects of releases of oil. The acute toxic response of marine biota to the oil, mortality to wildlife (birds, mammals, reptiles) caused by exposure to oil on the water surface and wildlife impacts are estimated by the biological effects model. French (2001) states that these estimates are derived from information on behavior and field observations of mortality computed as a function of temperature, toxic concentration, and time of exposure. Toxicity data for individual aromatics and an additive toxicity model (total toxicity is the concentration-weighted sum of toxicity from each compound) to estimate the toxicity of the aromatic mixture in the oil is used in the model. Lost productivity of lower trophic levels is translated up the food chain using a food web model. Also, fish and shellfish may be lost because habitats have been destroyed by oil.

Case studies: SIMAP was verified using the Exxon-Valdez oil spill in Prince William Sound in 1989 (French 2003) and the model algorithms provided reasonable results.

The biological effects model is sensitive to the assumed toxicity (LC50s), probability of oiling (including avoidance behavior), and biological abundances of the affected species. Toxicity values are easily determined but the degree of sensitivity to oil hydrocarbons of many species is unknown. Biological abundances are also difficult to estimate. French (2003) concluded that more detailed and quantitative information on bird and other wildlife behavior in the presence of oil would greatly improve ability to estimate impacts from spills. Understanding of population and/or ecosystem structure and dynamics is necessary for successful modeling of the biological impacts of oil spills.

OILMAP and SIMAP were both used to predict the transport and fate of the North Cape Spill off the Rhode Island coast in 1996. One of the conclusions of Spaulding *et al.* (1996) was that the extent of

the toxic plume was consistent with the limited field data available and the observed pattern of dead lobsters and shellfish along the coastline.

As also mentioned in section 4.3 of this report, **OSCAR** is another commercial oil spill model which includes exposure models for fish and ichthyoplankton (Reed *et al.* 1995a, 1996a), birds, and marine mammals (Downing and Reed 1996). As stated on SINTEF's website, oil and chemical databases supply chemical and toxicological parameters required by the model. Results of model simulations are stored at discrete time-steps in computer files, which are then available as input to one or more biological exposure models. The algorithms used to simulate the processes controlling physical fates of substances are described in Aamo *et al.* (1993) and Reed *et al.* (1994, 1995a, b).

Case studies: The OSRI (Oil Spill Research Institute) PWS-NC/FC (Prince William Sound Nowcast/Forecast system) was designed to include biological and ecosystem model components, but these components are not yet developed. At the PWS Biological Modeling Workshop in 2003 the decision was made to focus on modeling the biology of Pacific herring as it was well enough understood to permit this. A schematic of the PWS model is presented in **Appendix 2.**

6.0 OTHER ISSUES

6.1 DEMONSTRATION RUNS AND COMPUTING REQUIREMENTS

In order to provide some indication of the relative accuracy and economy of POM and ROMS, grids were created for the Queen Charlotte region and simple circulation studies were carried out. The same 5 km grid that was used for the internal tide studies of Cummins and Oey (1997) was employed for the POM simulations. This grid was rotated 30° counterclockwise to better align with the coastline and had dimensions 90×160 in the rotated reference frame. The vertical resolution consisted of 20 sigma levels. A second grid with the same resolution but different alignment was also created for ROMS. Though in theory ROMS grids can also be rotated, it was recommended (Di Lorenzo, pers. comm.) that this not be done as it can cause problems in the subsequent model setup and runs. The ROMS grid was created with the Matlab script SEAGRID and it covers the region between 47° and 57°N and 126° and 138°W. In this case the grid dimensions were larger, 165×223. In the vertical, 30 terrain-following S-coordinates, with parameters were $\theta_s = 5$, $\theta_b = 0.4$, and $Tcline = 200$m, were chosen to give increased resolution in the surface and bottom layers.

Bathymetry was taken from the ETOPO5 and the Canadian Hydrographic Service databases. In order to minimize spurious flows that can result from sharp bathymetric changes over neighbouring grid cells (Haney 1991), the ROMS bathymetry was smoothed with a Shapiro filter that is part of the ROMS Matlab toolbox, while the POM bathymetry was smoothed with a technique recommended in Blumberg and Mellor (1987). The original and smoothed ROMS bathymetries are shown in **Figures 2 and 3**. In order to confirm that these spurious flows were under control, a simple ROMS test was performed with realistic vertical profiles of temperature and salinity and no wind, tidal, or boundary forcing. As the horizontal density field is horizontally uniform initially and there is no forcing, there should be no baroclinic pressure gradients and no circulation or sea surface setup should develop throughout the run. Nevertheless, as pointed out by Haney (1991), numerical errors associated with the use of terrain-following coordinates in the presence of steep bathymetry can cause spurious pressure gradients and flows. In this case, after running ROMS for one month nonzero surface currents developed but were less than 0.5 cm/s everywhere except for on the west coast of the Queen Charlotte Islands and Vancouver

Islands, where they ranged from 1 to 2 cm/s. The associated sea surface height was less than 1 cm everywhere. Though not perfect, these results were deemed to be acceptable.

The actual ROMS tests included following forcing scenarios:

i) A constant 10m/s wind from the southeast, meant to crudely represent typical winter conditions.

ii) Interpolated mean winter wind-stress field from buoy data in the Queen Charlotte Region from 1987-1995, as shown in **Figure 4**.

iii) Case ii) winds along with tidal forcing that was obtained by interpolating height and current harmonics for the four constituents M_2, K_1, O_1, and S_2 from the Foreman *et al.* (2000) model for the northeast Pacific Ocean.

As the POM model grid is smaller both horizontally and vertically, it was less expensive to run. Thirty-day simulations on the same Alpha workstation took 4 hours and 12 hours for POM and ROMS, respectively. However ROMS does have an MPI version that has been tested on the multi-processor cluster at IOS, so it is capable of running more quickly on another platform. On the other hand, though POM also has an MPI version, it is neither supported nor regularly updated like ROMS. So it remains to be seen if the POM computation time could be improved. In any event, a 5 km grid is inadequate for capturing the detailed circulation patterns that would be required for oil and gas and/or ecosystem simulations in the Hecate LOMA region. A grid with horizontal resolution of the order of 1 km would be much better. Without multi-processor capabilities, running a grid with such a resolution would take 125 as long as the 5 km grid simulations and thus be impractical on desktop machines. Unless IOS cluster performance can be improved beyond the maximum factor-of-four speedup over desktops that testing revealed in early 2005, it is clear that IOS will need new computing facilities to meet any demands that North coast oil and gas (or other compute-intensive projects) will require.

Unfortunately there was not sufficient time to carry out an extensive comparison between the POM and ROMS simulations. The following commentary therefore only describes some preliminary results. As time and funding permit, further testing will continue.

Both the POM and ROMS simulations had similar features. In spite of the fact that winter winds were consistently part of all forcing, no Haida eddies were generated. This is somewhat puzzling as the Di Lorenzo *et al.* (2005) simulations that studied the generation of these eddies had similar winter forcing and were performed on an even coarser 8 km grid. However when tidal forcing was included in the simulations, the Rose Spit Eddy was evident with both models, substantiating the Bowman *et al.* (1992) claim that this feature arises from baroclinic tidal rectification. **Figure 5** is a close-up of the subtidal currents at 50m depths arising from the ROMS simulation. The Rose Spit Eddy and counterclockwise circulation around Hecate Strait are clearly evident. **Figure 6** shows the cooler upwelled waters that arise on the eastern side of the Queen Charlotte Islands in this same simulation, while **Figure 7** shows the surface currents arising from the POM simulation with average winter winds.

6.3 OTHER CONSIDERATIONS

The Royal Society Report identified a need for more current observations in the Hecate LOMA region. Though extensive current meter and drifter observations have been made through previous programs such as the PERD Project of the early 1990s (Crawford *et al.* 1995), there are few observations of near-bottom and winter currents. Filling these gaps will not only provide more information on the expected transport of drilling wastes and potential oil spills in winter, but they will also provide a more complete archive for validating future circulation models.

In order to provide better design criteria for offshore drilling structures, a surface wave model should also be developed and coupled to a circulation model. Additional observations would also be needed to validate this model. Diane Masson is the IOS expert in surface wave modelling and clearly she should be involved in the development, evaluation, and coupling of such a model.

Finally, both the circulation and surface wave models would benefit from a high resolution atmospheric model that could provide detailed wind and surface flux forcing. This is particularly true near the coast where topographic steering can be expected to change wind direction significantly from that further offshore. Present Environment Canada atmospheric models for the Hecate LOMA region have a coarse resolution and can only capture large scale features. An MM5 model with resolution of at least 4km, such as that developed by Cliff Mass and colleagues at the University of Washington or Roland Stull and his group at the University of British Columbia, would greatly improve the accuracy of the atmospheric forcing for the two north coast ocean models. (The UW model is presently being used to provide forcing for a circulation model that has been developed for hindcasting and forecasting the circulation off the entrance of Juan de Fuca Strait.) The regional office of Environment Canada is aware of this need and looking into procuring the necessary funding to make it happen.

7.0 SUMMARY AND RECOMMENDATIONS

In terms of recommending a model to simulate the circulation in the Hecate LOMA region, both POM and ROMS fulfil all the requirements. Though SELFE has the advantage of an irregular grid that could provide a much better representation of the complicated coastal features including the inside passage, its numerical techniques are inferior to those of POM and ROMS. Quite simply, it is not sufficiently accurate. POM has been extensively applied throughout the world and has several IOS users. Though it does not have as many 'bells and whistles' as its newer competitor ROMS, it has proven accuracy and has been coupled to oil spill, sediment transport, biological, and surface wave. ROMS, though seemingly more difficult to set-up and use, has many more built-in features than POM and its recent versions have been specifically designed to take advantage of multi-processing computer architecture. And though it has fewer IOS users, there are several US users in the Northeast Pacific that can be (and already have been) called upon for advice. ROMS has not yet been coupled to an oil spill model but this is expected to happen soon in Alaska and possibly California. In addition, ROMS does have built-in biophysical coupling that has already been applied to the California current system (Powell *et al.* 2005) and is presently under development (Angelica Pena at IOS) for the Juan de Fuca region.

So in terms of a specific recommendation for a circulation model, we feel that it comes down to a question of philosophy. Should we pick proven (POM) or new (ROMS) technology? The lead author (MF) feels that ROMS is the model of the future and leans in that direction. But his co-authors may feel differently and DFO, in its ongoing investigations into developing a national policy for operational oceanography (John Loder, pers. comm.), seems to be leaning toward yet another model, the French system OPA, whose accuracy has yet to be fully evaluated in shelf regions.

As for an oil spill model recommendation, though there is little IOS experience with these models we feel that either OILMAP or OSCAR would do an adequate job. The specific choice may be determined by industry, based on their experience in other applications. Similarly for a drilling mud model, we feel that MUDMAP seems to be the best choice but defer to industry and/or the greater experience of our colleagues at BIO, if and when the actual selection has to be made.

For an ecological model, we feel that the built-in biophysical coupling offered by ROMS and a growing experience with these coupled models in the Northeast Pacific tilt the scales in that direction. Such a choice would seem to add further weight to the argument for also choosing ROMS as the circulation model.

REFERENCES

Aamo, O.M., Reed, M. and Daling, P.S. 1995. Evaluation of environmental consequences and effectiveness of oil spill response operations with a possible change in first line response at the Veslefrikk field. IKU Report No. 95.006.

Aamo, O.M., Reed, M. and Downing, K. 1996. Calibration, verification, and sensitivity analysis of the SINTEF oil spill contingency and response (OSCAR) model system. Report No.42.4048. 87 p.

Aamo, O.M., Reed, M., Daling, P.S. and Johansen, Ø. 1993. A Laboratory-based weathering model: PC version for coupling to transport models. Proceedings of the 1993 Arctic and Marine Oil Spill Program (AMOP) Technical Seminar. pp. 617-626.

Alexeeva, I., Schrum, C., and St. John, M. 2003. A Coupled Bio-physical Model HAMSOM-ECO for the North Sea Frontal Regions. Geophysical Research Abstracts 5: 13165.

Allen, J.S. 2002. Progress on physical circulation and ecosystem modeling in the COAST and WEST programs. AGU 2002 Fall Meeting, San Francisco, California.

Al Rabeh, A.H., Lardner, R.W., Gunay, N., and Hossain, M. 1995. OILPOL - An oil fate and transport model for the Arabian Gulf. Proc. Fourth Saudi Eng. Conf. King Abdul-Aziz Univ Press, Jeddah. pp. 415-427.

ASA/Martec Joint Venture.1996. Remote Sensing of Environmental Parameters: Final Report 1996. Canadian Coast Guard Rescue and Environmental Branch. Halifax, NS. 112 p.

ASCE Task Committee. 1996. State-of-the-art review of modeling transport and fate of oil spills. J. Hydraulic Engineer. 122: 294-609.

Baird, M.E., Oke, P.R., Suthers, I.M., and Middleton, J.H. 2004. A plankton population model with biomechanical descriptions of biological processes in an idealized 2-D ocean basin. J. Mar. Systems 50: 199-222.

Ballantyne, V.A., Foreman, M.G.G., Crawford, W.R., and Jacques, R. 1996. Three-dimensional model simulations for the north coast of British Columbia. Cont. Shelf Res. 16: 1655-1682.

Baptista, A.M., Zhang, Y., Chawla, A., Zulauf, M., Seaton, C., Myers, E., Kindle, J., Wilkin, M., Burla, M., and Turner, P.J. 2005. A cross-scale model for 3D baroclinic circulation in estuary-plume-shelf systems: II. Application to the Columbia River. Cont. Shelf Res. 25 (7-8): 935-972.

Baptista, A.M., Zhang, Y., Chawla, A., Zulauf, M.A., Seaton, C., Myers, E.P., Kindle, J., Wilkin, M., Burla, M., and Turner, P.J. 2004. CORIE modeling system: status of hindcast simulations as of May 2004. Center for Coastal and Land-Margin Research, Oregon Health & Science Univ. 57 p.

Blumberg, A.F., and Mellor, G.L. 1987. A description of a three-dimensional coastal circulation model. *In* Three Dimensional Coastal Ocean Models, Coastal and Estuarine Ser., vol. 4. Edited by N. S. Heaps. AGU. Washington, D.C. p. 1-16.

Boudreau, P.R., Gordon, D.C., Harding, G.C., Loder, J.W., Black, J., Bowen, W.D., Campana, S., Cranford, P.J., Drinkwater, K.F., Van Eeckhaute, L., Gavaris, S., Hannah, C.G., Harrison, G., Hunt, J.J., McMillan, J., Melvin, G.D., Milligan, T.G., Muschenheim, D.K., Neilson, J.D., Page, F.H., Pezzack, D.S., Robert, G., Sameoto, D., and Stone, H. 1999. The possible environmental impacts of petroleum exploration activities on the Georges Bank ecosystem. Can. Tech. Rep. Fish. Aquat. Sci. 2259: iv + 106 p.

Bougeault, P. 2003. The WGNE survey of verification methods for numerical prediction of weather elements and severe weather events. CAS/JSC Working Group on Numerical Experimentation (WGNE) 18: 10 p.

Bowman, M.J., Visser, A.W., and Crawford, W.R. 1992. The Rose Spit Eddy in Dixon Entrance: Evidence for its existence and underlying dynamics. Atmos. Ocean 30(1): 70-93.

Brovchenko, I., Kuschan, A., Maderich, V., and Zheleznyak, M. 2002. The modeling system for simulation of the oil spills in the Black Sea. Abstracts Book of the 3rd EuroGOOS Conference. Athens, Greece.

Cherniawsky, J., and Crawford, W.R. 1996. Comparison between weather buoy and Comprehensive Ocean-Atmosphere Data Set wind data for the west coast of Canada. J. Geophys. Res. 101(C8): 18,377-18,389.

Cherniawsky, J., Wang, K., Titov, V., Stephenson, F., and Rabinovich, A. 2004. Predicted Tsunami Heights and Currents in Vancouver Island Harbours Caused by a Future Cascadia Subduction Zone Earthquake. [Abstract]. EOS AGU Trans. 85(17): p JA290.

Cherniawsky, J.Y., Foreman M.G.G., Crawford, W.R., and Henry, R.F. 2001. Ocean Tides from TOPEX/ POSEIDON sea level data. J. Atmos. Oceanic Tech. 18(4): 649-664.

Coastal Center of the UCLA Institute of the Environment, The Coastal and Marine Geology Program. 2003. Application of the Regional Ocean Modeling System (ROMS) to Water and Sediment Quality Issues in the Southern California Bight. U.S. Geological Survey 14 p.

Committee on Oil in the Sea. 2003. Oil in the Sea III: Inputs, Fates, and Effects. National Academies Press, Washington, D.C. USA. 280 p. Available online at *http://www.nap.edu/books/0309084385/html/*

Cox, W., and Cooney, T. 2003. Prince William Sound Nowcast-Forecast & Biological Modeling Workshops Report. Anchorage, Alaska.

Cranford, P.J., Gordon, D.C., Hannah, C.G., Loder, J.W., Milligan, T.G., Muschenheim D.K., and Shen, Y. 2001. Modelling effects on scallop populations from potential petroleum exploration drilling on northeastern Georges Bank. Can. J. Fish. Aquat. Sci. (to be submitted).

Crawford, W. R. 2002b. Physical Characteristics of Haida Eddies. J. Oceanogr. 58(5): 703-713.

Crawford, W.R. 2001. Oceans of the Queen Charlottes Islands, 2001. CD-ROM. Can. Tech. Rep. Fish. Aquat. Sci. 2383: 1CD-ROM.

Crawford, W.R., and Whitney, F. 1999b. Mesoscale eddies aswirl with data in Gulf of Alaska Ocean. EOS, Transactions of the American Geophys. Union 80(33): 365-370.

Crawford, W., Cretney, W., Cherniawsky, J., and Hannah, C. 2002a. Modelling Oceanic Fates of Oil, Drilling Muds and Produced Water from the Offshore Oil and Gas Industry, with Application to the Queen Charlotte Basin. Can. Sci. Advisory Secretariat Res. Doc. 2002/120. 54 p.

Crawford, W.R., Cherniawsky, J.Y., Foreman, M.G.G., and Gower, J.R.R. 2002c. Formation of the Haida-1998 oceanic eddy. J. Geophys. Res. – Oceans 107(C7): 6-11.

Crawford W.R., Cherniawsky, J.Y., and Cummins, P.F. 1999a. Surface currents in British Columbia waters: Comparison of observations and model predictions. Atmos. Ocean 37: 255-280.

Crawford, W.R., Cherniawsky, J.Y., Cummins, P.F., and Foreman, M.G.G. 1998a. Variability of tidal currents in a wide strait: A comparison between drifter observation and numerical simulations. J. Geophys. Res. 103: 12,743-12,759.

Crawford, W.R., Cherniawsky, J.Y., Hannah, C.G., and Ballantyne, V.A. 1996: Current predictions for oil spill models. Spill Science & Technology Bull. 3: 235-239.

Crawford, W.R., Woodward, M.J., Foreman, M.G.G., and Thomson, R.E. 1995. Oceanographic features of Queen Charlotte Sound and Hecate Strait in the summer. Atmos. Ocean 33: 639-681.

Cretney, W.J., Crawford, W., Masson, D., and Hamilton, T. 2002. Physical oceanographic and geological setting of a possible offshore oil and gas industry in the Queen Charlotte Basin. Can. Sci. Advisory Secretariat Res. Doc. 2002/004. Fisheries and Oceans Canada, Nanaimo, British Columbia. 38 p.

Cummins, P.F., and Oey, L.Y. 1997. Simulation of barotropic and baroclinic tides off northern British Columbia. J. Phys. Oceanog. 27: 762-781.

Cummins, P.F., Cherniawsky, J.Y., and Foreman, M.G.G. 2001. Internal tide generation along the Aleutian Ridge. J. Mar. Res. 59(2): 167-191.

Curchitser, E., Haidvogel, D., Hermann, A.Y., Dobbins, E., and Powell, T. 2005. Multi-scale modeling of the North Pacific Ocean I: Assessment and analysis of simulated basin-scale variability (1996-2003). J. Geophys. Res. In press.

Curchitser, E., Haidvogel, D., Hermann, A.Y., Dobbins, E., and Powell, T. 2004. A numerical simulation of large-scale physical events in the North Pacific Ocean during the 1997-2003 period. PICES XIII Annual Meeting. Hawaii, U.S.A. S9-1993.

Daling, P.S., and Brandvik, P.J. 1991. Characterization and prediction of the weathering properties of oils at sea. A manual for the oils investigated in the DIWO project, DIWO 16, IKU Sintef Group. Continental Shelf and Petroleum Technology Research Institute, Trondheim, Norway, 1991.

Daling, P.S., Brandvik, P.J., Mackay, D., and Johansen, Ø. 1990. Characterization of crude oils for environmental purposes. Oil & Chemical Pollution 7: 199-224.

Denman, K.L., and Pena, M.A. 1999. A coupled 1-D biological/physical model of the northeast subarctic Pacific Ocean with iron limitation. Deep-Sea Res. II 46: 2877-2908.

deYoung, B., Heath, M., Werner, F., Chai, F., Megrey, B., and Monfray, P. 2004. Challenges of Modeling Ocean Basin Ecosystems. Science 304(5676): 1463-1466.

Di Lorenzo, E., Foreman, M.G.G., and Crawford, W.R. 2005. Modeling the Generation of Haida Eddies. Deep Sea Res. II 52: 853-873.

Dobbins, E.L., Hermann, A.J., Hinckley, S., Stabeno, P., and Kachel, N. 2004. Use of a 3D model to investigate residence times over Portlock Bank near Kodiak, AK. EPOC 2004 presentation. Sidney, BC.

Dodimead, A.J. 1980. A general review of the oceanography of the Queen Charlotte – Hecate Strait – Dixon Entrance region. Can. Manuscr. Rep. of Fish. Aquat. Sci. 1574: 248 p.

Downing, K., and Reed, M. 1996. Object-oriented migration modeling for biological impact assessment. Ecol. Model. 93: 203 - 219.

Drozdowski, A., Hannah, C.G., and Tedford, T. 2004. bblt Version 7.0 User's Manual. Can. Tech. Rep. Hydrogr. Ocean Sci. 240: vi + 69 p.

Ezer, T. 2001. Comparisons of Numerical Aspects in POM and ROMS. 2001 Users' Workshop: Second joint biannual Terrain-following modeling communities (POM, ROMS, SCRUM, SPEM) meeting, Boulder, Colorado, USA.

Ezer, T., Arango, H., and Shchepetkin, A.F. 2002. Developments in terrain-following ocean models: intercomparisons of numerical aspects. Ocean Model. 4: 249-267.

Fasham, M.J.R., Ducklow, H.W., and McKelvie, S.M. 1990. A nitrogen-based one-D model of plankton dynamics in the oceanic mixed layer. J. Mar. Res. 48: 591-639.

Fernandes, L.A. 2004. Coupled Biological-Physical Modeling. Discussion Group for MMS Planning Chair. Louisiana-Texas (LATEX) continental shelf in the Gulf of Mexico. Seventh International Marine Environmental Modeling Seminar. [online] *http://www.sintef.no/imems2004/session_biological.htm* (accessed 14 July, 2004).

Fiechter, J., and Mooers, C. 2004. Numerical Simulations of Florida Current Frontal Eddies With Implications For Mesoscale Biophysical Processes and Fisheries Oceanography. ASLO/TOS Ocean Research 2004 Conference. Honolulu, Hawaii.

Foreman, M.G.G. 2004c. ELCIRC Applications to British Columbia Waters. ELCIRC Users Group First Annual Meeting. OGI School of Science & Engineering. Portland, Oregon

Foreman, M.G.G. 1978. Manual for tidal currents analysis and prediction. Pacific Marine Science Report 78-6: 70 p.

Foreman, M.G.G., Stucchi, D., Zhang, Y., and Baptista, A.M. 2005. Circulation models for the Broughton Archipelago. In preparation.

Foreman, M.G.G., Hickey, B., Di Lorenzo, E., MacFadyen, A., and Trainer, V. 2004a. Modeling and Observational Studies of the Juan de Fuca Eddy. Presentation at the AGU Ocean Sciences Meeting. Portland, Oregon.

Foreman, M.G.G., Di Lorenzo, E., Hickey, B., and MacFadyen, A. 2004b. Revisiting the Juan de Fuca Eddy: Modelling and Observational Studies. Presentation at the Canadian Meteorological and Oceanographic Society Annual Meeting. Edmonton, Alberta.

Foreman, M.G.G., Di Lorenzo, E., Morrison, J., Li, J.Y., Hickey, B., MacFadyen, A., and Trainer, V. 2004d. Ocean circulation modelling in support of ECOHAB PNW. Presentation at the 11th International Conference on Harmful Algae. Cape Town, SA.

Foreman, M., Hickey, B., Trainer, V., MacFadyen A., and Di Lorenzo, E. 2003. Preliminary modelling and observational studies of the Juan de Fuca Eddy. PICES XII Annual Meeting. Seoul, Republic of Korea.

Foreman, M.G.G., Crawford, W.R., Cherniawsky, J.Y., Henry, R.F., and Tarbotton, M. 2000a. A high-resolution assimilating tidal model for the northeast Pacific Ocean. J. Geophys. Res. 105(C8): 19,665–19,698.

Foreman, M.G.G., Smith, C.L., and Chandler, P. 2000b. Current simulations and biological transport for the western continental margin of Vancouver Island. Proceedings of the XIII International Conference on Computational Methods in Water Resources.

Foreman, M.G.G., Crawford, W.R., Cherniawsky, J.Y., Gower, J. F.R., Cuypers, L., and Ballantyne, V.A. 1998. Tidal correction of TOPEX/POSEIDON altimetry for seasonal sea surface elevation and current determination off the Pacific coast of Canada. J. Geophys. Res. 103(C12): 27,979-27,998.

Foreman, M.G.G., Henry, R.F., Walters, R.A., and Ballantyne, V.A. 1993. A finite element model for tides and resonance along the north coast of British Columbia. J. Geophys. Res. 98:2,509-2,531.

French-McCay, D.P. 2004. Running Head: Oil spill impact assessment modeling. Environmental Toxicology and Chemistry Manuscript 03-382. Chemistry 23(10): 42 p.

French, D. 2001. Modeling oil spill impacts. In: State of the Art in Oil Modelling and Processes. Edited by R. Garcia- Martinez and C. Brebbia. WIT Press, Southampton, UK. p 23-50.

French, D. 1998. Modeling the impacts of the North Cape oil spill. Proceedings: Twenty-First Arctic and Marine Oilspill Program (AMOP) Technical Seminar. Edmonton, Alberta, Canada. p. 387-430.

French-McCay, D.P. and Isaji, T. 2004. Evaluation of the consequences of chemical spills using modeling: chemicals used in deepwater oil and gas operations. Facilitating Constructive Government-Industry Interactions. Environ. Model. Software 19(7-8): 629-644.

Frost, B.W. 1993. A modeling study of processes regulating plankton standing stock and production in the open subarctic Pacific Ocean. Prog. Oceanogr. 32:17-56.

Gan, J., and Allen, J.S. 2002. Modeling study of upwelling processes over the Oregon shelf. EOS Trans. AGU, 83(47). OS62A-0228.

Gilbert, T. 2000. The Oil Spill Response Atlas and Introduction of a New Oil Spill Trajectory Model. Australian Maritime Safety Authority. Presentation at Spillcon 2000. Australia.

Gordon Jr., D.C., Cranford, P.J., Hannah, C.G., Loder, J.W., Milligan, T.M., Muschenheim, D.K., and Shen, Y. 2000. The potential effects of exploratory hydrocarbon drilling on Georges Bank scallop populations. Can. Tech. Rep. Fish. Aquat. Sci. 2317: 116 p.

Gower J., and Jones, D.M. 1994. Canadian west coast giant waves. Mariners Weather Log (Spring): 4-8.

Haidvogel D.B., and Beckman, A.1998. Numerical Models of the Coastal Ocean. *In* The Sea (10). Edited by Kenneth H. Brink and Allan R. Robinson. John Wiley & Sons, New York, NY. p. 457-482.

Haigh, S.P, Denman, K.L., and Hsieh, W.W. 2001. Simulation of the planktonic ecosystem response to pre- and post-1976 forcing in an isopycnic model of the North Pacific. Can. J. Fish. Aquat. Sci. 58: 703-722

Haney, R.L. 1991. On the pressure gradient force over steep topography in sigma coordinate ocean models. J. Phys. Oceanogr. 21: 610-619.

Hannah, C. 2004. An Assessment Model for the Fate and Environmental Effects of Offshore Drilling Discharge. SCOR Canadian Ocean Science Newsletter 11: 3-4.

Hannah, C.G., Xu, Z., Shen, Y., and Loder, J.W. 1998. A model for suspended sediment transport in the benthic boundary layer. *In* Estuarine and Coastal Modeling. Proc. 5th Intern. Confer., Amer. Soc. Civil Engin., New York. p.708-722.

Hannah, C.G., Loder, J.W., and Shen, Y. 1996. Shear dispersion in the benthic boundary layer. *In* Estuarine and Coastal Modeling. Proc. 4th Intern. Confer. Edited by M.L. Spaulding and R.T. Cheng. Amer. Soc. Civil Engin., New York. p. 454-465.

Hannah, C.G., Shen, Y., Loder, J.W., and Muschenheim, D.K. 1995. bblt: Formulation and exploratory applications of a benthic boundary layer transport model. Can. Tech. Rep. Hydrogr. Ocean Sci. 166: vi + 52 p.

Hannah, C.G., LeBlond, P.H., Crawford, W.R., and Budgell, W.P. 1991. Wind-driven barotropic circulation in Queen Charlotte Sound and Hecate Strait. Atmos. Ocean 29: 712-736.

Hermann, A.J., Curchitser, E.N., Haidvogel, D.B., and Dobbins, E.L. 2004. A comparison of remote versus local influence of El Niño on the coastal circulation of the Northeast Pacific. PICES XIII Annual Meeting. Honolulu, Hawaii, U.S.A.

Hermann, A.J., Haidvogel, D.B., Dobbins, E.L., Hinckley, S., Stabeno, P.J., Musgrave, D., and Hedstrom, K. 2003. Nested Biophysical Modeling of the Coastal Gulf of Alaska: Inferences from Circulation Results. Presented at Marine Science in the Northeast Pacific, Joint Science Symposium, Achorage, Alaska.

Hermann, A.J., Haidvogel, D.B., Dobbins, E.L., Hinckley, S., and Stabeno, P.J. 2002. Interannual variability of SST and cross-shelf transport in the coastal Northeast Pacific. U.S. GLOBEC NEP-CCS SI Meeting. Corvallis, OR.

Hermann, A.J., Hinckley, S., Megrey, B.A., and Napp, J.M. 2001. Applied and theoretical considerations for constructing spatially explicit Individual-Based Models of marine fish early life history which include multiple trophic levels. ICES J. Mar. Sci. 58(5): 1030-1041.

Hodgins, D.O., Huang, J.H., and Fingas, M.F. 1992. Oil spill modelling using remote sensed surface currents. Proceedings of the Fifteenth Arctic and Marine Oilspill Program (AMOP), Edmonton. Alberta. pp. 381-405.

Hofmann, E.E. 1998. Overview: Predictive Modeling for Marine Ecosystems. American Geophysical Union 1998 Fall Meeting. San Francisco, California. Session OS11E-04.

Hofmann, E.E., and Friedrichs, M.A. 2002. Predictive modeling for marine ecosystems. *In* The Sea (12). Edited by Allan R. Robinson, James J. McCarthy and Brian J. Rothschild. John Wiley & Sons, New York, NY. pp. 537-565.

Hood, R.R., Kohler, K.E., McCreary, J.P., and Smith, S.L. 2003. A four-dimensional validation of a coupled physical–biological model of the Arabian Sea. Deep Sea Research Part II: Topical Studies in Oceanography 50(22): 2917-2945.

IPCC, 2001: Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Integovernmental Panel on Climate Change. Edited by R. T. Watson and the Core Writing Team. Cambridge University Press, Cambridge, UK, and New York, NY. 398 p.

Ito, S., Kishi, M.J., Kurita, Y., Oozeki, Y., Yamanaka, Y, Mengrey, B., and Werner, F.E. 2004. Initial design for a fish bioenergetics model of Pacific saury coupled to a lower trophic ecosystem model. Fish. Oceanogr. 13(1): 111-124

Jacques Whitford Environment Limited (JWEL). 2001. British Columbia Offshore Technology Update. BC Ministry of Energy and Mines. 196 p.

Jacques, R. 1997. Modelling the Circulation of Northern British Columbia Waters.Thesis (Ph. D.) University of British Columbia, Vancouver, B.C. 240 p.

Jarosz, E., and Blain, C.A. 2004. Internal Tides in the Bab el Mandab Strait. ELCIRC Users Group First Annual Meeting. OGI School of Science & Engineering. Portland, Oregon.

Johnsen, S., Frost, T.K., Hjelsvold, M., and Utvik, T.R. 2000. Environmental Impact Factor - a proposed tool for produced water impact reduction, management and regulation. Presentation at the SPE International Conference on Health, Safety, and the Environment in Oil and Gas Exploration and Production. Stavanger, Norway. SPE 61178.

Kishi, M.J., Okunishi, T. and Yamanaka, Y. 2004. A Comparison of Simulated Particle Fluxes Using NEMURO and Other Ecosystem Models in the Western North Pacific. J. Oceanogr. 60(1): 63-73.

Kochergin, I.E., and Bogdanovsky, A.A. 2004. Oil spill simulation based on VOS models. Pacific Oceanography 2(1-2): 126-134.

Kochergin, I.E. Bogdanovsky, A.A., Budaeva, V.D., Makarov, V.G., Mishukov, V.F., Ovsienko, S.N., Putov, V.F., Reitsema, L.A., Sciallabba, J.W., Sergucheva, O.O., and Yarosh, P.V. 1999. Modeling of oil spills for the shelf conditions of northeastern Sakhalin. Proceedings of the Second PICES Workshop on the Okhotsk Sea and Adjacent Areas. Nemuro, Japan.

Korotenko, K.A., Mamedov, R.M., and Mooers, C.N.K. 2001. Prediction of the Transport and Dispersal of Oil in the South Caspian Sea Resulting from Blowouts. J. Environ. Fluid Mechanics 1(4): 383-414.

Kurapov, A.S., Allen, J.S., Egbert, G.D., Miller, R.N., and Erofeeva, S.Y. 2004. Data Assimilation in Shelf Circulation Models. Office of Naval Research [online report]. http://www.coas.oregonstate.edu/research/po/research/kurapov/overview_2004_Nov.html (accessed 14 July, 2005).

Kurapov, A.S., Allen, J.S., Egbert, G.D., Kosro, P.M., Levine, M.D., and Boyd, T. 2002. Data Assimilative Studies of Coastal Circulation off Oregon. EOS Trans. AGU, 83(47). OS71F-02.

Lardner, R.W., Zodiatis, G., Loizides, L., and Demetropoulos, A.1998. An Operational Oil Spill Model in the Levantine Basin. International Symposium on Marine Pollution. Monaco.

Large, W.G., McWilliams, J.C., and Doney, S.C. 1994. Oceanic vertical mixing: A review and a model with a nonlocal k-profile boundary layer parameterization. Rev. Geophys. 32: 363-403.

Mackas, D.L., and Galbraith, M.D. 2002. Zooplankton Distribution and Dynamics in a North Pacific Eddy of Coastal Origin: I. Transport and Loss of Continental Margin Species. J. Oceanogr. 58(5): 725-738.

MacLaren Plansearch (1991) Limited.1993. Wind and Wave Climate Atlas Volume IV: The West Coast of Canada. Transport Canada Report TP10820E, Halifax.

Marchesiello, P., McWilliams, J.C., and Shchepetkin, A. 2001. Open boundary conditions for long-term integration of regional ocean models. Ocean Model. 3:1-20.

Marshall, J., Adcroft, A., Hill, C., Perelman, L., and Heisey, C. 1997. A finite-volume, incompressible Navier Stokes model for studies of the ocean on parallel computers. J. Geophys. Res. 102 (C3): 5753-5766.

Masson, D. 1996. A case study of wave-current interaction in a strong tidal current. J. Phys. Oceanogr. 26: 359-372.

Masson, D., and Cummins, P.F. 2004. Observations and modeling of seasonal variability in the Straits of Georgia and Juan de Fuca. J. Mar. Res. 62: 491-516.

Masson, D., and Cummins, P.F. 1999. Numerical simulations of a buoyancy-driven coastal countercurrent off Vancouver Island. J. Phys. Oceanogr. 29(3): 418-435.

MacCready, P., and Geyer, W.R. 2001a. Estuarine salt flux through an isohaline surface. J. Geophys. Res. 106(C6): 11629-11637.

McCreary, J.P., Kohler, K.E., Hood, R.R., Smith, S., Kindle, J., Fischer, A.S. and Weller, R.A. 2001b. Influences of diurnal and intraseasonal forcing on mixed-layer and biological variability in the Arabian Sea. J. Geophys. Res. 106: 7139-7155.

Megrey, B.A., Rose, K., Hay, D., and Werner. F, 2003. A Coupled Lower and Higher Trophic Level Marine Ecosystem Model of the North Pacific Ocean Including Pacific Herring. Presentation, PICES XII Annual Meeting. Seoul, the Republic of Korea.

Mellor, G.L. 2003. Users guide for a three-dimensional, primitive equation, numerical ocean model. Princeton University, Princeton, NJ. 53 pp.

Mellor, G.L. 1973. Analytic prediction of the properties of stratified planetary surface layers. J. Atmos. Sci. 30: 1061-1069.

Mellor, G.L., and Blumberg, A.F. 1985. Modeling vertical and horizontal diffusivities with the sigma coordinate system. Mon. Wea. Rev.113: 1380-1383.

Mellor, G.L., and Yamada, T. 1982. Development of a turbulence closure model for geophysical fluid problems. Rev. Geophys. Space Phys. 20: 851-875.

Mellor, G.L., and Yamada, T. 1974. A hierarchy of turbulence closure models for planetary boundary layers. J. Atmos. Sci. 31: 1791-1806.

Miller, A.J., Di Lorenzo, E., Neilson, D.J., Kim, H.-J., Capotondi, A., Alexander, M.A., Bograd, S.J., Schwing, F.B., Mendelssohn, R., Hedstrom K., and Musgrave, D. L. 2005. Interdecadal changes in mesoscale eddy variance in the Gulf of Alaska circulation: Implications for the Steller sea lion decline. Atmosphere-Ocean. In press.

Moisan, J.R., and Hofmann, E.E. 1996. Modelling nutrient and plankton processes in the California coastal transition zone 3. Lagrangian drifters. J. Geophys. Res. 101: 22677–22691.

Moore, A.M., Arango, H.G., Miller, A.J., Cornuelle, B.D., Di Lorenzo, E., and Neilson, D.J. 2004. A Comprehensive Ocean Prediction and Analysis System Based on the Tangent Linear and Adjoint Components of a Regional Ocean Model. Ocean Model. 7: 227-258.

Morrison, J., Robinson, C., and Foreman, M.G.G. 2004.Tracking Biological Particles Using Elcirc. ELCIRC Users Group First Annual Meeting. OGI School of Science & Engineering. Portland, Oregon.

Myers, E. 2004. Using ELCIRC in NOAA's Coastal Storms Initiative. ELCIRC Users Group First Annual Meeting. OGI School of Science & Engineering. Portland, Oregon.

Myers, E., and Aikman, F. 2003. A forecast circulation model of the St. Johns River, Florida. *In* Estuarine and Coastal Modeling: Proceedings of the Eighth International Conference on Estuarine and Coastal Modeling. Edited by Malcolm L. Spaulding, P.E. Monterey Bay, CA. p. 144-156.

Niu, H. 2003. Transport Properties of Discharged Synthetic Based Drilling Wastes. Thesis (M.Eng.) Memorial University of Newfoundland, St. John's, NL.

Oey, L.-Y., Mellor, G.L., and Hires, R.I. 1985a. A three-dimensional simulation of the Hudson-Raritan estuary. Part I: Description of the model and model simulations. J. Phys. Oceanogr. 15: 1676-1692.

Oey, L.-Y., Mellor, G.L., and Hires, R.I. 1985b. A three-dimensional simulation of the Hudson-Raritan estuary. Part II: Comparison with observation. J. Phys. Oceanogr. 15: 1693-1709.

Olascoaga, M.J., Idrisi, N., and Romanou, A. 2005. Biophysical isopycnic-coordinate modelling of plankton dynamics in the Arabian Sea. Ocean Model. 8(1-2): 55-80.

Oliveira, A., Fortunato, A., and Baptista, A.M. 2000. Mass Balance in Eulerian-Lagrangian Transport Simulations in Estuaries. ASCE J. Hydraulic Engineer. 126(8): 605-614.

Patin, S. 1999. Environmental Impact of the Offshore Oil and Gas Industry. EcoMonitor Publishing, New York, U.S.A. 425 p. [Translated from Russian by Elena Cascio].

Peña, M.A. 2003. Modelling the response of the planktonic food web to iron fertilization and warming in the NE subarctic Pacific. Prog. Oceanogr. 57: 453-479.

Petro-Canada. 1983. Offshore Queen Charlotte Islands: Initial Environmental Evaluation. Environment Canada and Ministry of Environment, Lands and Parks Canada. 3 volumes.

Pinto, L., de Oliveira, A., and Fortunato, A.B. 2004. Applications of ELCIRC at LNEC: stratification in the Guadiana estuary and tidal propagation in the Obidos lagoon. ELCIRC Users Group First Annual Meeting. OGI School of Science & Engineering. Portland, Oregon.

Pinto, L.L., Oliveira, A., Fortunato, A.B., and Baptista, A.M. 2003. Analysis of the stratification in the Guadiana estuary. *In* Estuarine and Coastal Modeling: Proceedings of the Eighth International Conference on Estuarine and Coastal Modeling. Edited by Malcolm L. Spaulding, P.E. Monterey Bay, CA. ASCE. p.1094-1113.

Powell, T., Lewis, C., Curchitser, E., Haidvogel, D., Hermann, A., and Dobbins, E. 2005. Results from a three-dimensional, nested biological-physical model for the California Current System and comparisons with statistics from satellite imagery. J. Geophys. Res. In press.

Reed, M., Johansen, O., Brandvik, P.J., Daling, P., Lewis, A., Fiocco, R., Mackay, D., and Prentki, R. 1999. Oil Spill Modeling towards the Close of the 20th Century: Overview of the State of the Art. Spill Science & Technology Bull. 5(1): 3-16.

Reed, M., Aamo, O.M., and Downing, K. 1996a. Calibration and Testing of IKU's Oil Spill Contingency and Response (OSCAR) Model System. Proceedings of the 19th Arctic and Marine Oilspill Program (AMOP) Technical Seminar. Calgary, Alberta, Canada. p. 689-726.

Reed, M., Johnsen, S., Melbye, A., and Rye, H. 1996b. PROVANN. A model system for assessing potential chronic effects of produced water. *In* Produced Water 2. Environmental Issues and Mitigation Technologies. Edited by M. Reed and S. Johnsen. Plenum Press, New York. pp. 317-330.

Reed, M., Aamo, O.M., and Daling, P.S. 1995a. Quantitative analysis of alternate oil spill response strategies using OSCAR. Spill Science & Technology Bull. 2(1): 67-74.

Reed, M., French, D., Rines, H., and Rye, H. 1995b. A three-dimensional oil and chemical spill model for environmental impact assessment. Proceedings of the 1995 International Oil Spill Conference. Long Beach, CA. p. 61-66.

Reed, M., Turner, C., and Odulo, A. 1994. The role of wind and emulsification in modeling oil spill and surface drifter trajectories. Spill Science & Technology Bull. 1: 143–157.

Royal Society of Canada (RSC). 2004. Report of the Expert Panel on Science Issues Related to Oil and Gas Activities, Offshore British Columbia, Natural Resources Canada. 155 p.

Robertson, R., Beckmann, A., and Hellmer, H. 2003. M-2 tidal dynamics in the Ross Sea. Antarctic Science 15(1): 41-46.

Robertson, R., and Beckmann, A. 2001. A Comparison of POM and ROMS for Modeling Internal Tides in Weak Stratification. Second joint biannual Terrain-following modeling communities (POM, ROMS, SCRUM, SPEM) meeting, Boulder, Colorado, USA.

Robinson, A.R., and Lermusiaux, P.F.J. 2002. Data Assimilation for Modeling and Predicting Coupled Physical-Biological Interactions in the Sea. *In* The Sea (12). Edited by Allan R. Robinson, James J. McCarthy and Brian J. Rothschild. John Wiley & Sons, New York, NY. p. 475-536.

Robinson, A.R., Lermusiaux, P.F.J., and Sloan III, N.Q. 1998. Data Assimilation. *In* The Sea (10). Edited by Kenneth H. Brink and Allan R. Robinson. John Wiley & Sons, New York. p 541-594.

Robinson, C.L.K., Morrison, J., and Foreman, M.G.G. 2005. Oceanographic connectivity among marine protected areas on the north coast of British Columbia, Canada. Can. J. Fish. Aquat. Sci. 62: 1350-1362.

Sabeur, Z.A., and Tyler, A.O. 2003. Validation and application of the PROTEUS model for the physical dispersion, geochemistry and biological impacts of produced waters. Environ. Model. Software 19(7-8): 717-726.

Sea-Air-Land Modeling and Observing Network (SALMON): The Coastal Gulf of Alaska Circulation Model (3-km grid). [online article] http://halibut.ims.uaf.edu:8000/~salmon (accessed 14 July 2005)

Semtner, A. 1995. Modeling ocean circulation. Science 269: 1397-1385.

Shchepetkin, A., and McWilliams, J.C. 2005. The Regional Oceanic Modeling System(ROMS): A split-explicit, free-surface, topography-following-coordinate ocean model. Ocean Model. 9(4): 347-404.

Shchepetkin, A.F., and McWilliams, J.C. 2003. A method for computing horizontal pressure-gradient force in an ocean model with a non-aligned vertical coordinate. J. Geophys. Res. 108(C3): 35.1-35.34.

Shchepetkin, A., and McWilliams, J.C. 1998. Quasi-monotone advection schemes based on explicit locally adaptive dissipation. Monthly Weather Review 126: 541-1580.

Shulman, I., and Rochford, P.A. 2000. Boundary Conditions in the Pacific West Coast Princeton Ocean Model of CoBALT. Naval Research Lab Stennis Space Center MS. A499973. Storming Media, Washington, DC. 19 p.

Smith, C.L., Hill, A.E., Foreman, M.G.G., and Peña, M.A. 2001. Horizontal transport of marine organisms resulting from interactions between diel vertical migration and tidal currents off the west coast of Vancouver Island. Can. J. Fish. Aquat. Sci. 58(4): 736-748.

Song, Y. and Haidvogel, D.B. 1994. A semi-implicit ocean circulation model using a generalized topography-following coordinate system. J. Comp. Physiol. 115: 228-244.

Southern California Coastal Ocean Observing System (SCCOOS). 2004. [Online information] 2 p. http://www.sccoos.org/docs/SCCOOS-Products.pdf (accessed 14 July, 2005)

Spaulding, M.L. 1995. Oil spill trajectory and fate modeling: state-of-the-art review. Proceedings of the Second International Oil Spill Research and Development Forum. London, U.K. p. 508-516.

Spaulding, M.L., Bishnoi, P.R., Anderson , E., and Isaji, T. 2000. An integrated model for prediction of oil transport from a deep water blowout. 23rd Arctic and Marine Oil Spill Program (AMOP) Technical Seminar. Vancouver, British Columbia, Canada, p. 611-636.

Spaulding, M.L., Anderson, E., Howlett, E., Mendelsohn, D., and Opishinski, T. 1996. Application of OILMAP and SIMAP to Predict the Transport and Fate of the North Cape Spill, Narragansett, RI. Proceedings of the 19th Arctic and Marine Oilspill Program (AMOP) Technical Seminar, 1996, Calgary, Alberta, Canada. (1): 745-774.

Spitz, Y.H., Gan, J., and Allen, J.S. 2002. Three-dimensional response of the ecosystem to upwelling off the Oregon Coast. EOS Trans. AGU, 83(47). OS62A-0240.

Stipa, T., Skogen, M., Hansen, I., Eriksen, A., Hense, I., Kiiltomäki, A., Søiland, H., and Westerlund, A. 2003. Short-term effects of nutrient reductions in the North Sea and the Baltic Sea as seen by an ensemble of numerical models. Meri 49: 43-70.

Stratford, K., and Haines, K. 2002. Modelling nutrient cycling during the eastern Mediterranean transient event 1987–1995 and beyond. Geophys. Res. Lett. *29*(3): 1035.

Strong, D., Gallagher, P., and Muggeridge, D. 2002. British Columbia Offshore Hydrocarbon Development: Report of the Scientific Review Panel. [online report] BC Minister of Energy and Mines. http://www.offshoreoilandgas.gov.bc.ca/reports/scientific-review-panel/ (accessed 14 July, 2005).

Tabata, S. 1980. An Inventory of Physical Oceanographic Information for the Waters of Queen Charlotte Sound, Hecate Strait and Dixon Entrance and their Vicinity. Pacific Marine Science Report 80-7. 47 p.

Thomson, R.E. 1981. Oceanography of the British Columbia Coast. Can. Spec. Pub. Fish. Aquat. Sci. 56: 291 p.

Thomson, R.E., and Crawford, W.R. 1997. Processes affecting sea level change along the coasts of British Columbia and the Yukon. *In* Responding to Global Climate Change in British Columbia and the Yukon, Volume I of the Canada Country Study: Climate Impacts and Adaptation. Environment Canada and British Columbia Ministry of Environment, Lands and Parks. p. 1-19.

Thomson, R.E., and Emery, W.J. 1986. The Haida current. J. Geophys. Res. 91: 845-861.

Thomson, R.E., and Wilson, R.E. 1987. Coastal countercurrent and mesoscale eddy formation by tidal rectification near an oceanic cape. J. Phys. Oceanogr. 17: 2096-2126.

Umlauf, L., and Burchard, H. 2003: A generic length-scale equation for geophysical turbulence models. J. Mar. Res. 61: 235-265.

Utvik, T. 1999. Chemical characteristics of produced water from four offshore oil production platforms in the North Sea. Chemosphere 39: 2593–2606.

Vavrek, M.C., Hunt, H., Vavrek, D.L., and Colgan III, W. 2004. Status of Oil Brine Spill Site Remediation. Presentation at the 11th Annual International Petroleum Environmental Conference (IPEC). Albuquerque, NM.

Walters, R.A. 1992. A 3D, finite element model for coastal and estuarine circulation. Cont. Shelf Res. 12: 83-102.

Wang, H., and Cho, J. 2004. Simulating Tidal Characteristics in the Chesapeake Bay using ELCIRC and UnTRIM. ELCIRC Users Group First Annual Meeting. OGI School of Science & Engineering. Portland, Oregon.

Wang, J., and Meibing, J. 2002. 3-D Ocean State Simulations for Ecosystem Applications from 1995-1998 in Prince William Sound, Alaska. Exxon Valdez Oil Spill Restoration Project Final Report (Restoration Project 00389), Chugach Development Corporation, Anchorage, Alaska.

Whitney, F., and Robert, M. 2002. Structure of Haida eddies and their transport of nutrient from coastal margins into the NE Pacific Ocean. J. Oceanogr. 58(5): 715-723.

Xu, Z., Hannah, C.G., and Loder, J.W. 2000a. A 3d shear dispersion model applied to Georges Bank. *In* Estuarine and Coastal Modelling. Proceedings of the Sixth International Conference. Edited by M. L. Spaulding and H. L. Butler. American Society of Civil Engineers. p. 581-596.

Xue, H., Chai, F., and Pettigrew, N.R. 1999. A model study of seasonal circulation in the Gulf of Maine. J. Phys. Oceanogr. 30:111-1135.

Zhang, J., and Baptista, A. 2004a. SELFE: is there a higher-order alternative? ELCIRC Users Group First Annual Meeting. OGI School of Science & Engineering. Portland, Oregon.

Zhang, Y., Baptista, A.M., and Myers, E.P. 2004b. A cross-scale model for 3D baroclinic circulation in estuary-plume-shelf systems: I. Formulation and skill assessment. Cont. Shelf Res. 24 (18): 2187-2214.

Zulauf, M. 2004. Heat exchange model in ELCIRC. ELCIRC Users Group First Annual Meeting. OGI School of Science & Engineering. Portland, Oregon.

TABLE 1. Summary of Processes Included in Oil Spill Models (coupled)

Process	1. GNOME-ADIOS2 (NOAA)	2. OSIS(BMT) http://www.bmtcordah.com/services/consultancy.aspx?id=41	3. OSRA (MMS) http://www.mms.gov/epd/sciences/osmp/	4. SIMAP (ASA)	5. VOS-RT	6. SL ROSS SLROSM
Dimensions	Near-surface	Near-surface	Near-surface	Entire water column	Entire water column	surface
Area	US locations	n/a	Gulf of Mexico	n/a	Russia NORTHEASTERN SAKHALIN SHELF	n/a
Circulation	Wind factor + background + stochastic uncertainty	Wind factor + background current + wave (Elliot and Wallace, 1989)	Surface ocean currents and the sea-level winds, both of which were generated by other computer models using many observations of relevant physical parameters.	External hydrodynamic model + wind factor (if not in hydro model)	Uses prognostic tidal current fields and NOAA NWS NCEP meteorological data input and preliminary processing used for construction of the prognostic surface wind fields (up to three days) for the surveyed area;	Vectors of surface currents, 3% prevailing wind speed; user input wind forecasts; map form surface currents
Horizontal dispersion	Fickian	Random walk based by Morales et al. (1997)	Optional	Heuristic method + spillets	Yes see (a)	Okubo 1971
Spreading	Modified Fay + wind component	None	None	Modified Mackay et al. (1980)	Fay, 1991; Zhurbas 1978	Modified Mackay et al. (1980) and Fay 1971
Emulsification	Eley (1988)	Mackay et al. (1980)	None	Mackay et al. (1982)	Yes? (Michoukov *et al.*, 1997).	Modified Zagorski & Mackay 1982
Vertical dispersion (entrainment)	Modified Delvigne and Sweeney 1988 Includes wave break and Langmuirs	CONCAWE (Van Oudenhaven et al., 1983)	None	Delvigne and Sweeney (1988)	Delvigne and Sweeney (1988), Lehr 2001	Modified Delvigne and Sweeney 1988 or modified Audunson 1980
Dissolution	None	None	None	Mackay and Leinonen (1977)		
Evaporation	Modified Payne (Jones, 1997)	Stiver and Mackay (1984)	None	Stiver and Mackay (1984)	Yes (Michoukov *et al.*, 1997).	Modified Stiver & Mackay (1983)
Oxidation	None	None	None	First order decay with heuristic components		
Sediment & settling	Payne (1987)	None	None	French et al. (1999)		
Subsurface release	None	None	None	Simple passive point source		
Coastal-interaction	All oil sticks	All oil sticks	All oil sticks	COZOIL (Reed and Gundlach, 1989)		
Other info			http://www.mms.gov/itd/pubs/2004/2004-026.pdf	Biological Exposure and Effects Model Environmental, Chemical and Biological Databases	ADIOS II oil database	

Adapted from table 4.6 in **http://books.nap.edu/openbook/0309084385/html/111.html#p20006ac09960111001**

TABLE 2. Summary of Processes Included in 6 Composite Models

Process	1. GNOME-ADIOS2 (NOAA)	2. OSIS(BMT) http://www.bmtcordah.com/services/consultancy.aspx?id=41	3. OSRA (MMS) http://www.mms.gov/epd/sciences/osmp/	4. SIMAP (ASA)	5. VOS-RT	6. SL ROSS SLROSM
Dimensions	Near-surface	Near-surface	Near-surface	Entire water column	Entire water column	surface
Area	US locations	n/a	Gulf of Mexico	n/a	Russia NORTHEASTERN SAKHALIN SHELF	n/a
Circulation	Wind factor + background + stochastic uncertainty	Wind factor + background current + wave (Elliot and Wallace, 1989)	Surface ocean currents and the sea-level winds, both of which were generated by other computer models using many observations of relevant physical parameters.	External hydrodynamic model + wind factor (if not in hydro model)	Uses prognostic tidal current fields and NOAA NWS NCEP meteorological data input and preliminary processing used for construction of the prognostic surface wind fields (up to three days) for the surveyed area;	Vectors of surface currents, 3% prevailing wind speed; user input wind forecasts; map form surface currents
Horizontal dispersion	Fickian	Random walk based by Morales et al. (1997)	Optional	Heuristic method + spillets	Yes see (a)	Okubo 1971
Spreading	Modified Fay + wind component	None	None	Modified Mackay et al. (1980)	Fay, 1991; Zhurbas 1978	Modified Mackay et al. (1980) and Fay 1971
Emulsification	Eley (1988)	Mackay et al. (1980)	None	Mackay et al. (1982)	Yes? (Michoukov *et al.*, 1997).	Modified Zagorski & Mackay 1982
Vertical dispersion (entrainment)	Modified Delvigne and Sweeney 1988 Includes wave break and Langmuirs	CONCAWE (Van Oudenhaven et al., 1983)	None	Delvigne and Sweeney (1988)	Delvigne and Sweeney (1988), Lehr 2001	Modified Delvigne and Sweeney 1988 or modified Audunson 1980
Dissolution	None	None	None	Mackay and Leinonen (1977)		
Evaporation	Modified Payne (Jones, 1997)	Stiver and Mackay (1984)	None	Stiver and Mackay (1984)	Yes (Michoukov *et al.*, 1997).	Modified Stiver & Mackay (1983)
Oxidation	None	None	None	First order decay with heuristic components		
Sediment & settling	Payne (1987)	None	None	French et al. (1999)		
Subsurface release	None	None	None	Simple passive point source		
Coastal-interaction	All oil sticks	All oil sticks	All oil sticks	COZOIL (Reed and Gundlach, 1989)		
Other info			http://www.mms.gov/itd/pubs/2004/2004-026.pdf	Biological Exposure and Effects Model Environmental, Chemical and Biological Databases	ADIOS II oil database	

Adapted from table 4.6 in http://books.nap.edu/openbook/0309084385/html/111.html#p20006ac09960111001

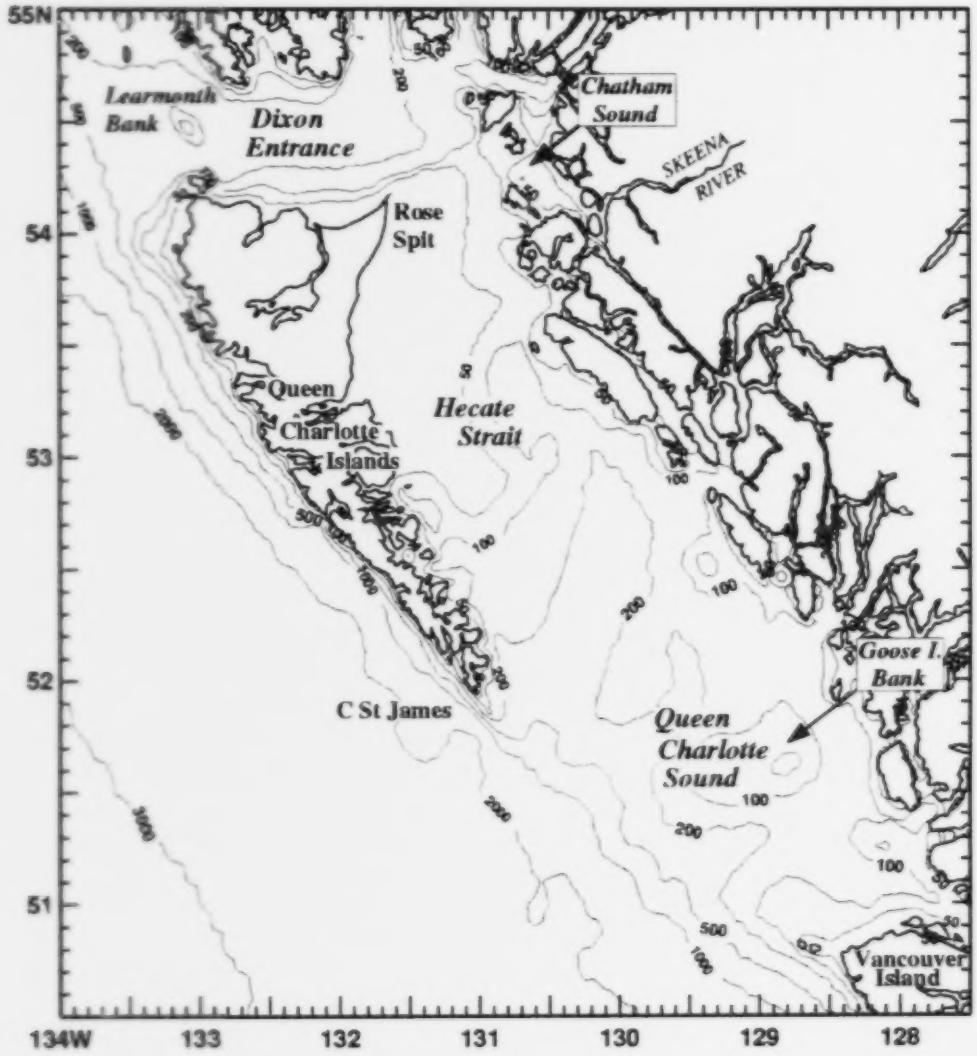


Figure 1. Map of the Queen Charlotte Basin (Crawford *et al.*, 2002a).

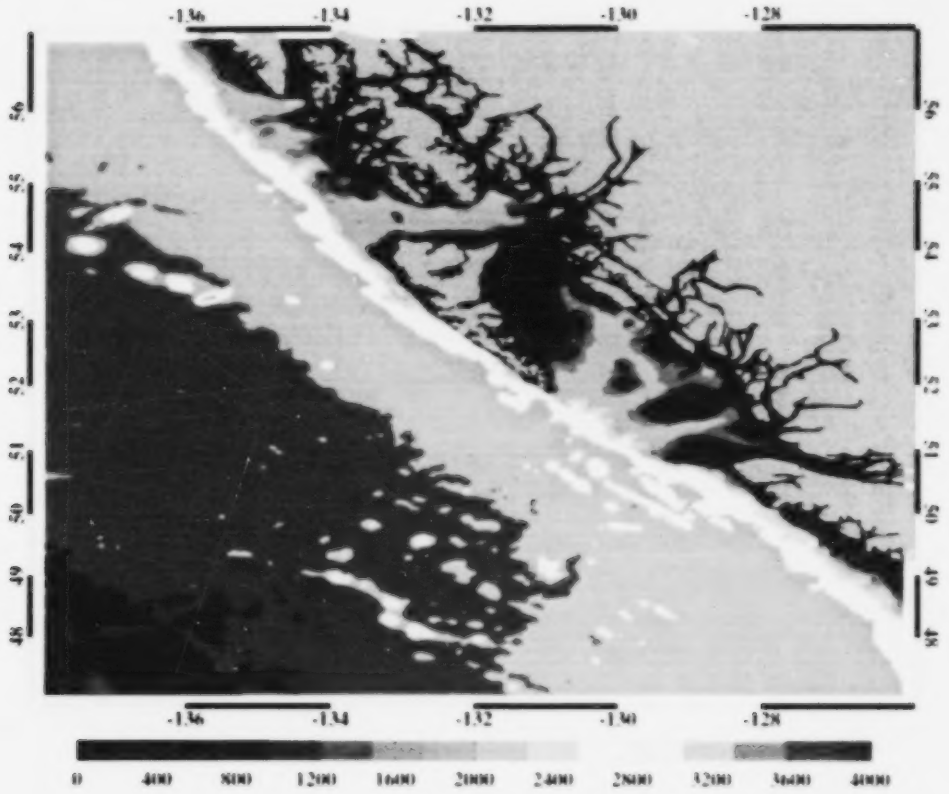


Figure 2. Raw bathymetry (m) for the Hecate LOMA region.

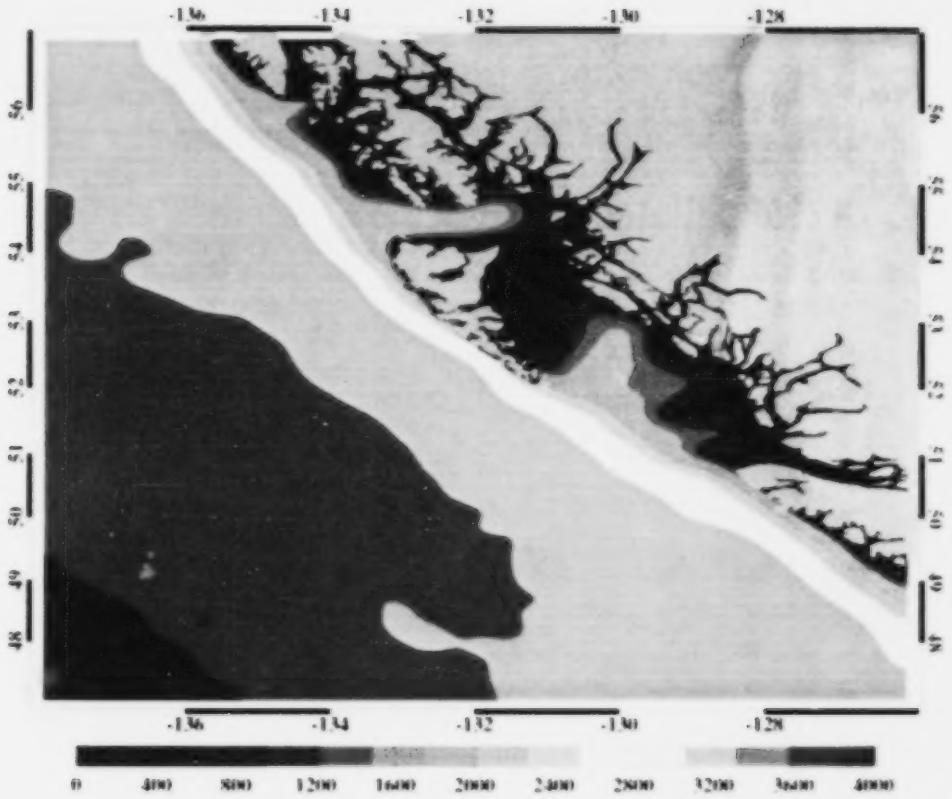


Figure 3. Smoothed bathymetry (m) for the ROMS model.

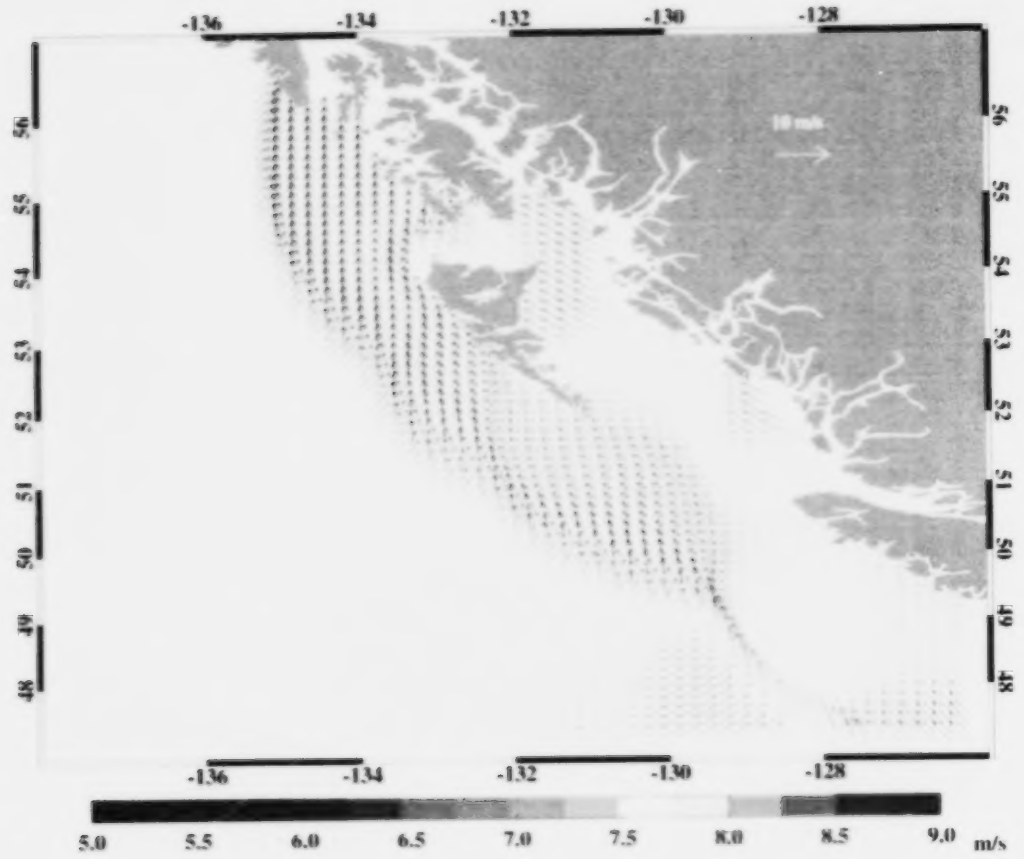


Figure 4. Average winter winds as interpolated from measurements at the Environment Canada offshore buoys.

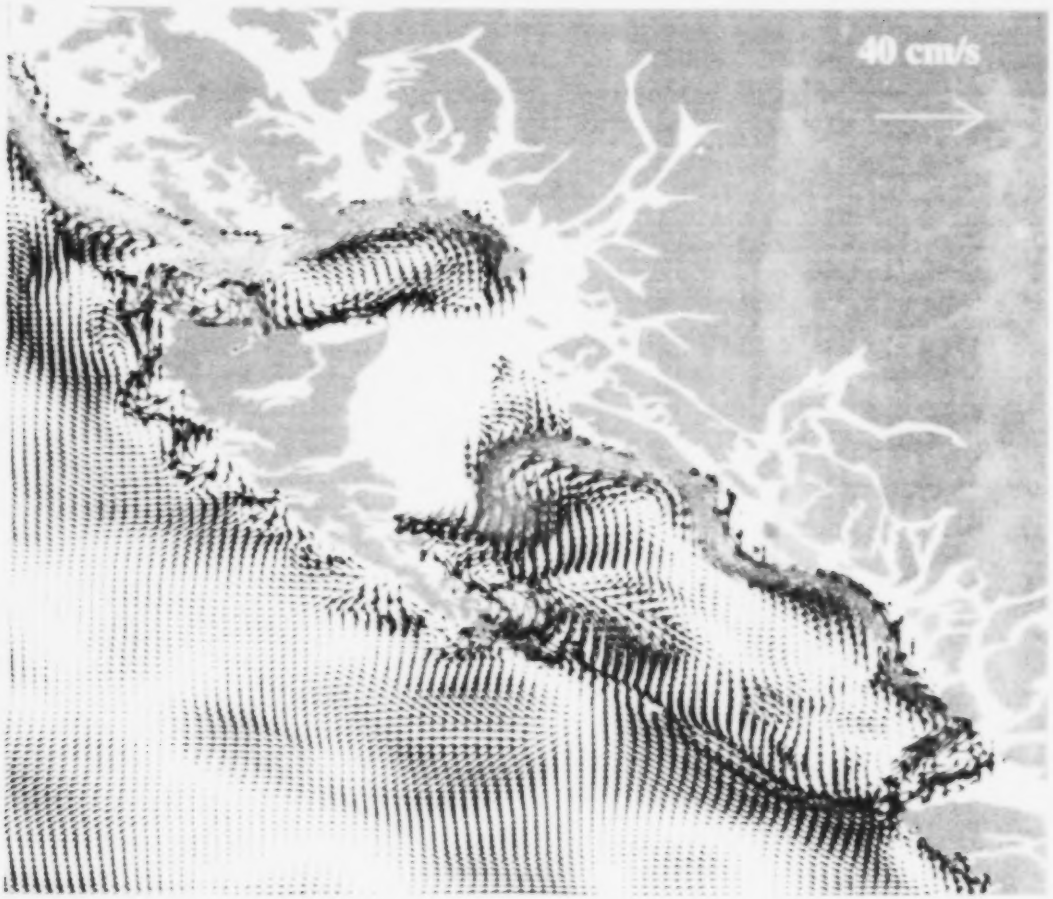


Figure 5. ROMS subtidal flows at 50m.

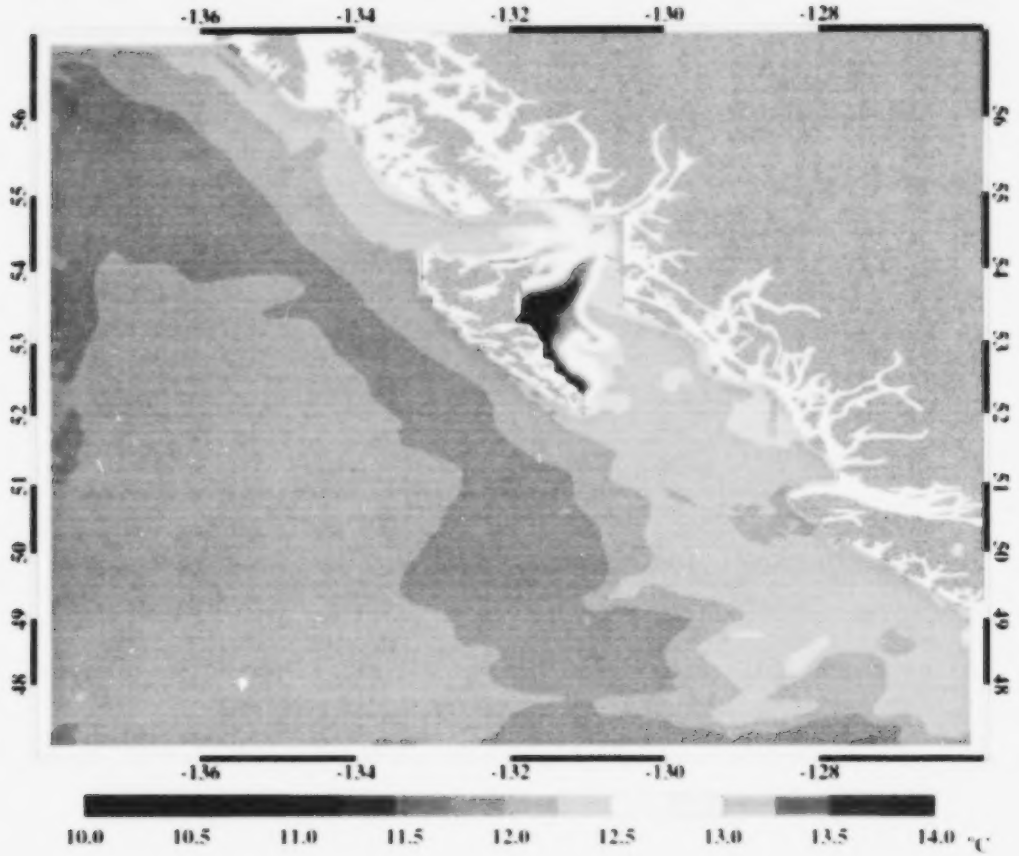


Figure 6. ROMS surface temperature with winter wind forcing.

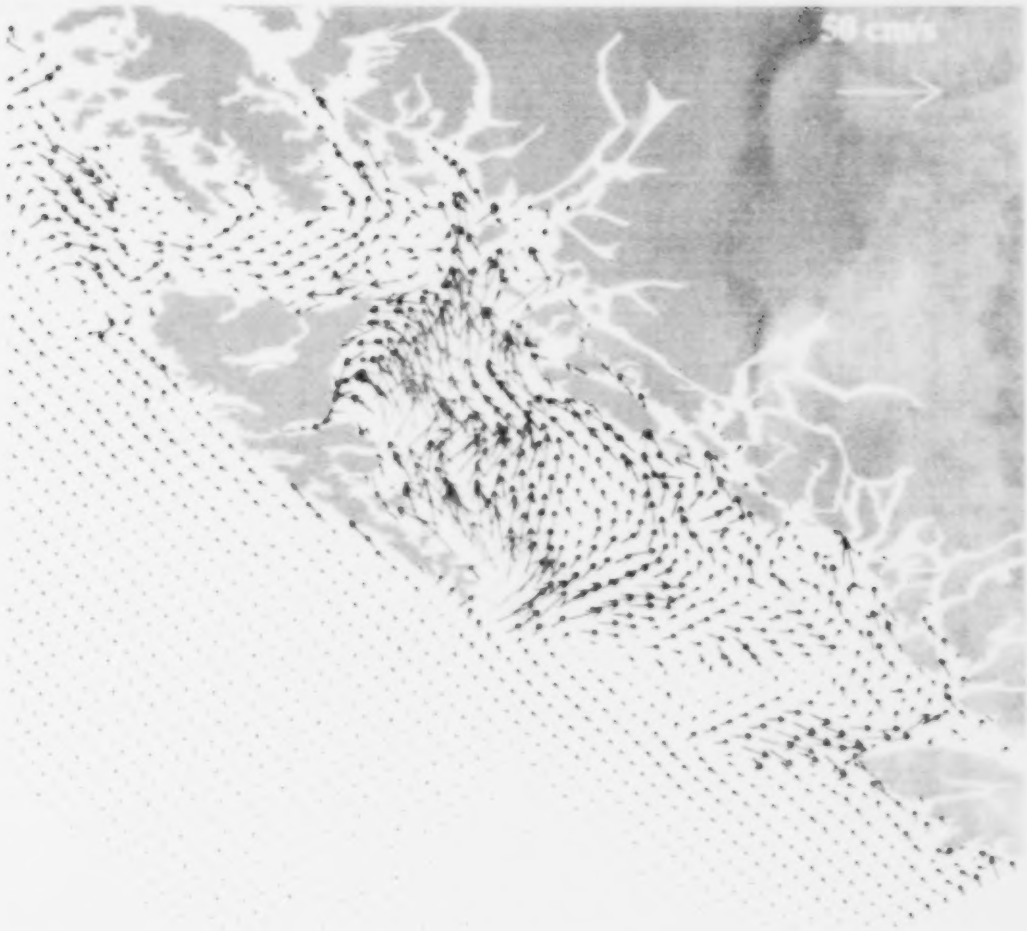


Figure 7. POM surface velocities with average winter wind forcing.

APPENDIX 1. Available Data

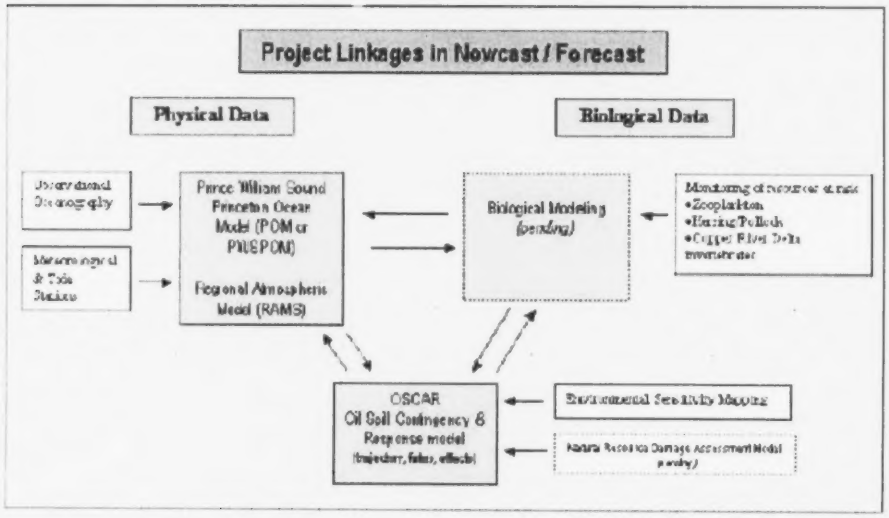
A wide range of data is available for the Queen Charlotte Basin. Here is a summary:

- **Satellite data including Seawifs, AVHRR** *http://www-sci.pac.dfo-mpo.gc.ca/osap/data/SearchTools/SearchSatellites_e.asp*
- **Lighthouse data: SST & SSS:** *http://www-sci.pac.dfo-mpo.gc.ca/osap/data/SearchTools/Searchlighthouse_e.htm*

  Bonilla Island (1960-Present) Latitude, Longitude = 53° 18'N, 130° 23'W;
  McInnes Island (1954-present) Latitude, Longitude = 52° 10'N, 128° 26'W;
  Langara Island (1936-present) Latitude, Longitude = 54° 9'N, 133° 2'W;
  Cape St. James (1934-1992) Latitude, Longitude = 51° 34'N, 131° 1'W
- **Weather Buoy data**: Tabular and graphical data are recorded hourly and provided via the National Data Buoy Center (NDBC), a part of the National Weather Service (NWS) of the National Oceanic and Atmospheric Administration; includes Wind Direction, Wind Speed, Wind Gust, Wave Height, Dominant Wave Period, Atmospheric Pressure, Pressure Tendency, Air Temperature, Water Temperature and Wind Chill. These stations are in the QCB region: http://www-sci.pac.dfo-mpo.gc.ca/osap/data/newbuoy/Buoy_location_details_e.htm

  WMO Identifier 46185 **Buoy name** South Hecate Strait
  WMO Identifier 46147 **Buoy name** South Moresby
  WMO Identifier 46208 **Buoy name** West Moresby
  WMO Identifier 46183 **Buoy name** North Hecate Strait
  WMO Identifier 46145 **Buoy name** Central Dixon Entrance
- **Temperature, salinity, transmissometer, nutrient, chlorophyll and oxygen** data is available from data collected during many oceanographic cruises in this area. http://www-sci.pac.dfo-mpo.gc.ca/osap/data/SearchTools/SearchProfiles_e.asp
- **Ocean drifter data:** A data report on CD-ROM, containing all data files http://www-sci.pac.dfo-mpo.gc.ca/osap/projects/QCI/qci_e.htm. This CD includes:
  - Loran-C drifter data: 3 and 10 metre depth
  - Argos drifter data
  - Currents measured at mooring sites

APPENDIX 2. Schematic of the PWS model from PWSNF Ws report.pdf



Prince William Sound
Oil Spill Recovery Institute